PRÁCTICAS DE MANEJO DEL OLIVAR, EFECTOS SOBRE LAS PROPIEDADES DEL SUELO E INFLUENCIA EN EL ALMACENAMIENTO Y SECUESTRO DE CARBONO

OLIVE GROVE MANAGEMENT PRACTICES, EFFECTS ON SOIL PROPERTIES AND INFLUENCE ON CARBON STORAGE AND SEQUESTRATION

Tesis Doctoral

Departamento de Química Agrícola, Edafología y Microbiología

Manuel González Rosado

UNIVERSIDAD DE CÓRDOBA

FACULTAD DE CIENCIAS UNIVERSIDAD DE CÓRDOBA

TITULO: *Prácticas de manejo del olivar, efectos sobre las propiedades del suelo e influencia en el almacenamiento y secuestro de carbono*

AUTOR: *Manuel González Rosado*

© Edita: UCOPress. 2021
Campus de Rabanales
Ctra. Nacional IV, Km. 396 A
14071 Córdoba

https://www.uco.es/ucopress/index.php/es/
ucopress@uco.es

UNIVERSIDAD DE CÓRDOBA

Programa de doctorado: (Recursos naturales y Gestión Sostenible)

Título de la tesis:

Prácticas de manejo en el olivar, efectos en las propiedades del suelo.

Olive grove management practices, effects on soil properties and influence on carbon storage and sequestration.

Directores: Luis Parras Alcántara

Beatriz Lozano García

Autor de la tesis: Manuel González Rosado

Fecha de depósito tesis en el Idep: 12/02/2021

TÍTULO DE LA TESIS: Prácticas de manejo del olivar, efectos sobre las propiedades del suelo e influencia en el almacenamiento y secuestro de carbono.

DOCTORANDO: Manuel González Rosado

INFORME RAZONADO DEL/DE LOS DIRECTOR/ES DE LA TESIS

(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

La presente Tesis Doctoral aborda la influencia de las prácticas de manejo (no laboreo) en las propiedades físicas y químicas de suelos de olivar de secano en áreas Mediterráneas. Para ello, se parte de una caracterización de los suelos (perfiles completos, con sus correspondientes horizontes) en una zona experimental de la provincia de Jaén. El efecto del manejo se realiza en zonas llanas y en zonas de ladera con diferentes posiciones topográficas (Toposecuencia), además se estudia su evolución a lo largo del tiempo (Cronosecuencia).

Inicialmente en la Tesis Doctoral se parte de un contexto global donde se analiza de forma detallada el papel de los suelos ante el cambio climático y su papel como almacén de CO_2. Posteriormente se analiza los factores y procesos que influyen en las dinámicas del carbono orgánico de los suelos agrícolas. Además, se realiza una revisión actual del estado del olivar en Andalucía, haciendo referencia a la importancia del cultivo, las diferentes tipologías, los problemas degradación (erosión hídrica) y los tipos de manejo predominantes.

A lo largo de esta memoria de Tesis se analiza el impacto de diferentes prácticas de manejo en suelos de olivar, mostrando sus debilidades y fortalezas tanto en largo como en corto plazo. Además, se han analizado las repercusiones en las propiedades físico - químicas de los suelos tras cambios de manejo como el paso de laboreo convencional a no laboreo o la inclusión de cubiertas vegetales en las calles de olivar. De este modo, la investigación que se desarrolla a lo largo de esta Tesis Doctoral es una fuente de conocimiento en la toma de decisiones por parte de los agricultores para el sistema de manejo de sus olivares, con lo que los resultados de esta Tesis Doctoral son una interesante herramienta para el sector olivarero andaluz.

Podríamos destacar de esta memoria de Tesis Doctoral su especial énfasis en las dinámicas del carbono orgánico en los suelos de olivar, analizando su distribución en profundidad (a lo largo del perfil) y en posiciones topográficas, así como los cambios en el *pool y stock* de carbono derivado del impacto de los diferentes manejos. La relevancia de los suelos como sumideros de carbono ha provocado que en los últimos años estén presentes en las diferentes estrategias que plantean la reducción de las emisiones de CO_2 y el almacenamiento de carbono. Con ello, en esta memoria de

Tesis Doctoral se muestra un estudio actual de la influencia de las prácticas de manejo en el contenido de carbono orgánico en los suelos de olivar.

De los resultados de la presente Tesis Doctoral se han derivado las siguientes publicaciones en revista de impacto:

Título: *Short-term effects of land management change linked to cover crop on soil organic carbon in Mediterranean olive grove hillsides.*

- Autores: González-Rosado, Manuel., Lozano-García, Beatriz., Aguilera-Huertas, Jesús., Parras-Alcántara, Luis.
- Science of The Total Environment *(2020 774.,140683).* https://doi.org/10.1016/j.scitotenv.2020.140683
- Base de Datos: ISI Web of Knowledge. Journal Citation Index.
- Área temática en la Base de Datos de referencia: Environmental Sciences.
- Índice de impacto de la revista en el año de publicación del Artículo: 6.551
- Lugar que ocupa/Nº de revistas del Área temática: 22/265 (Q1)

Título: *Long-term evaluation of the initiative 4‰ under different soil managements in Mediterranean olive groves.*

- Autores: González-Rosado, Manuel., Parras-Alcántara, Luis., Aguilera-Huertas, Jesús., Lozano-García, Beatriz.
- Revista: Science of The Total Environment *(2021 758.,143591).* https://doi.org/10.1016/j.scitotenv.2020.143591
- Base de Datos: ISI Web of Knowledge. Journal Citation Index.
- Área temática en la Base de Datos de referencia: Environmental Sciences.
- Índice de impacto de la revista en el año de publicación del Artículo: 6.551
- Lugar que ocupa/Nº de revistas del Área temática: 22/265 (Q1)

Título: *Effects of land management change on soil aggregates and organic carbon in Mediterranean olive groves.*

- Autores: González-Rosado, Manuel., Parras-Alcántara, Luis., Aguilera-Huertas, Jesús., Lozano-García, Beatriz.
- Revista: CATENA *(2020 195.,104840).* *https://doi.org/10.1016/j.scitotenv.2020.143591*
- Base de Datos: ISI Web of Knowledge. Journal Citation Index.
- Área temática en la Base de Datos de referencia: Water Resources.
- Índice de impacto de la revista en el año de publicación del Artículo: 4.333
- Lugar que ocupa/Nº de revistas del Área temática: 8/94 (Q1, D1)

POR TODO ELLO, SE AUTORIZA LA PRESENTACIÓN DE LA TESIS DOCTORAL.

Córdoba, 12 de febrero de 2021

Firma de los directores

Fdo.: Dr. Luis Parras Alcántara

PARRAS ALCANTARA LUIS - 26018489S

Firmado digitalmente por PARRAS ALCANTARA LUIS - 26018489S
Nombre de reconocimiento (DN): c=ES, serialNumber=IDCES-26018489S, givenName=LUIS, sn=PARRAS ALCANTARA, cn=PARRAS ALCANTARA LUIS - 26018489S
Fecha: 2021.02.12 11:31:31 +01'00'

Fdo.: Dra. Beatriz Lozano García

LOZANO GARCIA BEATRIZ - 44366161N

Firmado digitalmente por LOZANO GARCIA BEATRIZ - 44366161N
Fecha: 2021.02.12 12:03:11 +01'00'

Agradecimientos.

La Tesis doctoral que a continuación se desarrolla es el fruto de un largo periodo de dedicación y aprendizaje que quedan reflejados en este documento. En este proceso mucha gente ha sido participe y ha influido, sirvan estas líneas para reconocer a todos aquellos que de un modo u otro me han llevado a tener las capacidades para escribir esta Tesis Doctoral.

En primer lugar, han sido mis padres Pilar y Manuel los que han dedicado una vida de trabajo y esfuerzo para que la única preocupación de sus cuatro hijos fuera el aprendizaje. Con esta suerte que he tenido, ellos han sido la base de esta Tesis porque desde pequeño me han transmitido lo importante que es el conocimiento y su trabajo diario ha estado enfocado en que yo y mis hermanos pudiéramos tener las mejores condiciones posibles para el aprendizaje. Si esta Tesis Doctoral sirve por un momento para su satisfacción habrá merecido sobradamente la pena todo el esfuerzo de estos años.

He tenido la suerte de convivir con tres hermanos, Cristóbal, Sagrario y Pilar, ellos me han motivado y han hecho desarrollar mis capacidades, por eso esta Tesis también es de ellos. Junto a ellos he aprendido a vivir, me han hecho como persona y me han dado la lección más importante, valorar el estar junto a ellos.

Esta Tesis nunca habría sido posible sin mis directores Beatriz Lozano y Luis Parras. A ellos les debo la oportunidad que me dieron cuando hace tres años ahora me abrieron las puertas del Departamento de Química Agrícola, Edafología y Microbiología de la Universidad de Córdoba. Me depositaron su confianza y apostaron por mí para juntos sacar adelante dos retos tan importantes como el Proyecto europeo Diverfarming y la realización de esta Tesis. Por ello me siento un privilegiado, porque me han permitido hacer lo

que me gusta, investigar, aprender y enseñar. Junto a ellos en estos años he aprendido muchísimo, con Beatriz, didáctica y pedagógica, y con Luis, proactivo y resolutivo, a la vez que han ejercido de directores se han convertido en mis amigos con los que al mismo tiempo que corregimos artículos o vemos datos hablamos de nuestras familias, inquietudes o problemas.

Desde mi llegada al Departamento Concha Benítez me acogió en el ala sur. A ella también le debo mucho, ha dedicado gran parte de su tiempo a enseñarme de forma metódica pero cariñosa las técnicas del laboratorio con las que he trabajado en esta Tesis. Pero más importante aún ha sido su amistad, pues ha estado día tras día acompañándome dentro y fuera del laboratorio. En estos años me ha cuidado y se ha preocupado por mí, su apoyo ha sido fundamental.

Al niño de la casa, Jesús Aguilera, ya me lo encontré el primer día que llegué a Córdoba. Después hemos compartido muchos momentos de esta Tesis, con risas y bromas, pero también momentos complicados y horas de trabajo. Siendo muy diferentes congeniamos y trabajamos a gusto juntos para que esta Tesis y otros trabajos salgan adelante. Con su forma de ser consigue que haya buen ambiente y siempre tiene lista una conversación.

Agradecer al Departamento de Química Agrícola, Edafología y Microbiología de la Universidad de Córdoba con su directora Lourdes Moyano a la cabeza y a todos sus componentes María, Azahara, José Luis, Luis, Alberto, Inma, Zahira y María José por hacerme sentir como uno más desde el primer día de mi llegada y echarme una mano siempre que lo he necesitado.

Mis amigos cordobeses Juan Martín y Laura Castillo que siempre han estado disponibles para cualquier tema de esta Tesis u otra cosa que haya necesitado,

pero más importantes han sido porque son amigos con los que echar un vino, una comida o un rato de charla.

En estos agradecimientos también me acuerdo de alguien especial como María Luisa Gómez, maestra que me enseñó las puertas del conocimiento y del aprendizaje autónomo. Para mí es un referente, ser su alumno y trabajar con ella me mostró lo que era capaz de hacer y lo que quería ser, por ello le debo mi agradecimiento infinito.

Por último, pero no menos importante, quiero acordarme de mis amigos de EXTIERCOL, José, Heredia, Cristóbal y Pedro, sin ellos no podría estar donde estoy. Quien me conoce sabe lo importante que es para mí y lo orgulloso que estoy de proyecto EXTIERCOL, ya que es raro la conversación donde no lo nombro. Sin embargo, pocas veces nombro las personas que han hecho posible tantas satisfacciones ni lo mucho que he aprendido y disfrutado junto a ellos, en la huerta o en cualquier proyecto en los que nos hemos metido. Sé que esta Tesis les llena de alegría igual que sé que junto a ellos quedan muchas alegrías por vivir.

A todos mis agradecimientos, Manuel.

ABREVIATURAS

BD: Densidad aparente.

C: Carbono.

cPOM: Materia orgánica particulada gruesa.

CSR: Ratio de almacenamiento de carbono.

CT: Laboreo convencional.

DOC: Carbono orgánico disuelto.

DOM: Materia orgánica disuelta.

fPOM: Materia orgánica particulada fina.

GEIs: Gases efecto invernadero.

IPCC: Panel intergubernamental sobre el cambio climático.

MAOM: Materia orgánica asociada a la fracción mineral.

MBC: Carbono orgánico asociado a la biomasa microbiana.

MOC: Carbono orgánico asociado a la fracción mineral.

MWD: Diámetro medio ponderado.

NT: No laboreo.

NT+H: No laboreo con aplicación de herbicidas.

NT-CC: No laboreo con cubierta.

OC: Carbono orgánico.

PI: Índice de productividad.

POC: Carbono orgánico particulado.

POM: Materia orgánica particulada.

SOC: Carbono orgánico del suelo.

SOC-S: Stock de carbono orgánico del suelo.

SOM: Materia orgánica del suelo.

TN: Nitrógeno total.

TN-S: Stock de Nitrogeno.

TOC: Carbono orgánico total

WEOC: Carbono orgánico extraíble.

Resumen/ Summary

RESUMEN.

El papel de los suelos agrícolas está cobrando en los últimos años una importante relevancia social y gubernamental. Los suelos agrícolas han dejado de considerarse como meros soportes de plantas que producen alimentos y materias primas de diversa índole para ser considerados como un elemento central en la provisión de servicios ecosistémicos y en la mitigación del cambio climático.

El área Mediterránea se caracteriza por la vulnerabilidad y a la vez resiliencia de los ecosistemas que en ella se establecen. Esto la sitúa en un espacio clave ante las modificaciones que se derivan del cambio climático, como son el incremento de las temperaturas y el descenso de las precipitaciones. El olivar, como elemento característico de la cuenca mediterránea, tiene por delante el reto de conjugar unas cosechas estables y rentables para el agricultor con un manejo sostenible a largo plazo. Este reto es de especial importancia en Andalucía donde el olivar ocupa el 46% de las tierras de cultivo, forma parte ancestral de su cultura y su influencia social y económica traspasa con diferencia a la de cualquier otro cultivo.

Las prácticas de manejo de suelo asociadas a los cultivos son esenciales en la determinación de la capacidad del suelo para aportar servicios ecosistémicos. En este sentido, esta Tesis Doctoral se ha centrado en la evaluación de diferentes técnicas de manejo predominantes en olivar andaluz y el impacto que generan en las diferentes propiedades del suelo, prestando especial atención a su influencia en el secuestro y almacenamiento de carbono.

Además, esta evaluación se ha realizado en diferentes intervalos de tiempo (corto y largo plazo) analizando parámetros físicos y químicos de perfiles completos de suelo con profundidades aproximadas de 120 cm. Con ello se ha podido constatar la importancia de los horizontes profundos en las dinámicas de almacenamiento de carbono, puesto que en el área de estudio estos horizontes se acumulan aproximadamente el 50% del carbono orgánico del suelo. Conjuntamente con este análisis en profundidad, se ha determinado la influencia de la topografía y las fracciones de agregados en la distribución y secuestro de carbono.

El manejo del olivar en Andalucía se caracteriza principalmente por prácticas que implican el mantenimiento del suelo desnudo a lo largo del año. Estas prácticas implican un laboreo continuo y la aplicación de herbicidas (CT) o la ausencia de laboreo y el uso de herbicidas de pre y post emergencia (NT+H) para evitar la proliferación de flora arvense. Como consecuencia del uso de estas técnicas de manejo en el largo plazo (15 años) se ha podido comprobar un importante proceso de descarbonización de los suelos de olivar estudiados, con pérdidas en el *stock* de carbono que alcanzan los 28 Mg ha^{-1} en ambos manejos. Estos resultados sitúan a estos suelos lejos de cumplir los objetivos de incremento de carbono orgánico en los suelos agrícolas propuestos por la Iniciativa 4‰. Similar tendencia se ha registrado en el *stock* de nitrógeno con pérdidas de 6,2 Mg ha^{-1} para el laboreo convencional y 8,5 Mg ha^{-1} para el no laboreo con herbicidas. Relacionado con este proceso de pérdida de fertilidad estos manejos han arrojado importantes tasas de erosión, baja estabilidad estructural y pérdidas en la capacidad productiva de los suelos.

Una de las principales diferencias observadas entre ambos manejos se constató en la capacidad de infiltración. En el manejo NT+H se encontró un importante descenso en las ratios de infiltración con respecto al manejo CT. Esto fue relacionado con la formación de encostramiento superficial que limita la entrada de agua en el suelo y favorece los procesos de escorrentía.

La principal alternativa a estos manejos predominantes es la inclusión de cubiertas vegetales en las calles del olivar. En los dos años de evaluación, este sistema de manejo del suelo se ha mostrado como una técnica sostenible, con capacidad para reducir las tasas de erosión e incrementar las entradas de carbono en el suelo en algunas posiciones topográficas, con lo que puede influir positivamente en la calidad de los suelos a la vez que incrementa la productividad de los suelos de olivar. Sin embargo, en suelos deteriorados, en secano y con las condiciones climáticas estudiadas, la mejora de las propiedades edáficas es un proceso lento, desigual y fácilmente reversible. Esto se debe a que el desarrollo de la cubierta vegetal bajo estas condiciones no es sencillo pudiendo quedar en una vegetación poco desarrollada con escasa cobertura y generación de biomasa. Además, con la supresión del laboreo en este manejo también se cuantificó un descenso en la capacidad de infiltración de agua en el suelo, con lo que esto puede ser un importante hándicap para la instalación de este manejo, debido a un menor almacenamiento de agua en un medio con periodos constantes de déficit hídrico.

En conclusión, los resultados de esta Tesis muestran que el uso técnicas de manejo con suelo desnudo ha conducido a un deterioro en las propiedades de los suelos de olivar del área de estudio, afectando a la calidad de los suelos, poniendo en cuestionamiento su papel como facilitador de servicios ecosistémicos. La inclusión de cubiertas vegetales ha supuesto un cambio en esta tendencia, abriendo un camino hacia la regeneración de los suelos que debe constatarse en el largo plazo y donde la relación entre la cubierta y la disponibilidad de agua juegan un papel clave en el éxito de implementación de este manejo.

SUMMARY

The role of agricultural soils has acquired important social and governmental relevance in recent years. Agricultural soils are no longer considered as mere supports for plants that produce food and materials of diverse types, but nowadays as a central element in the ecosystem services provision and climate change mitigation.

The Mediterranean area is characterized by the vulnerability and resilience of its ecosystems. This situates it as a key area in the context of the variations resulting from climate change, such as higher temperatures and lower rainfall. The olive grove, as a representative element of the Mediterranean basin, faces the challenge of combining stable and profitable harvests for the farmer with long-term sustainable management. This challenge is particularly importance in Andalusia, where olive groves represent 46% of the cultivated land, is an ancient part of its culture, and their social and economic influence surpasses widely any other crop.

Soil management practices associated with crops are essential in determining the soil's capacity to provide ecosystem services. In this sense, this PhD Thesis has focused on the evaluation of different management techniques predominant in Andalusian olive groves and the impact generate on different soil properties, with special attention to their influence on carbon sequestration and storage.

In addition, this assessment has been carried out at different time intervals (short and long term) by analyzing physical and chemical parameters of complete soil profiles at depths of approximately 120 cm. This has confirmed the relevance of the deep horizons in the dynamics of carbon storage, since in the study area these horizons accumulate approximately 50% of the organic carbon in the soil. In combination with this in-depth analysis, the influence of topography and aggregate fractions on the distribution and sequestration of carbon has been determined.

Olive orchard management in Andalusia is mainly characterized by practices involving the maintenance of bare soil throughout the year. These practices imply continuous tillage and the application of herbicides (CT) or the absence of tillage and the use of pre- and post-emergence herbicides (NT+H) to prevent arvense flora proliferation. As a consequence of the use of these management techniques in the long term (15 years), a significant decarbonization process has been observed in the studied olive grove soils, with losses in the carbon stock of 28 Mg ha^{-1} in both managements. These results show that these soils are soils far from meeting the objectives of increasing organic carbon in agricultural soils proposed by the 4‰ Initiative. A similar trend has been registered in the nitrogen stock with losses of 6.2 Mg ha^{-1} for conventional tillage and 8.5 Mg ha^{-1} for no-tillage with herbicides. Related to this process of loss in the fertility levels, these management practices have resulted in significant erosion rates, low structural stability and losses in the productive capacity of the soils.

The main difference observed between the two management systems was observed in the infiltration capacity. A significant decrease in infiltration rates was found in the NT+H management compared to the CT management. This was related to the formation of surface crusting which limits the entry of water into the soil and promotes runoff processes.

The main alternative to these predominant management systems is the inclusion of vegetation covers in the olive grove alleys. In the two years of evaluation, this soil management system has been shown to be a sustainable technique, with the capacity to reduce erosion rates and increase soil carbon inputs in some topographic positions, thus positively influencing soil quality and increasing the productivity of olive grove soils. However, in deteriorated, rainfed soils and under the climatic conditions studied, the improvement of soil properties is a slow, uneven and easily reversible process. This is because the development of plant cover under these conditions is not easy and can result in poorly developed vegetation with little cover and biomass generation. In addition, with the elimination of tillage in this management, a decrease in the soil's water infiltration capacity was also quantified, which could be an important handicap for the installation of this management, due to a lower water storage in an environment with constant periods of water deficit..

In conclusion, the results of this thesis show that the use of bare soil management techniques has led to a deterioration in the properties of the olive grove soils in the study area, affecting soil quality and putting into question its role as a facilitator of ecosystem services. The inclusion of vegetation cover has changed this trend, opening a way towards soil regeneration that must be verified in the long term and where the relationship between cover and water availability plays a key role in the successful implementation of this management.

ÍNDICE

Resumen

1. Introducción……………………………………………………………….14

1.1. Los suelos agrícolas ante el cambio climático………………………………16

1.1.1. Ciclo del carbono y su influencia en el cambio climático…………….16

1.1.2. El papel de la agricultura como emisor y depósito de CO…………….19

1.1.3. La iniciativa 4 x 1000. El reto de los suelos agrícolas……………….23

1.1.4. La agricultura europea hacia la sostenibilidad ambiental…………….26

1.2. La materia orgánica del suelo, la esencia del agroecosistema……………….29

1.2.1. La materia orgánica del suelo, un elemento complejo………………..29

1.2.2. Fracciones de la materia orgánica……………………………………30

1.2.3. La materia orgánica del suelo y su rol en la provisión de servicios ecosistémicos en los suelos agrícolas……….………………………32

1.3. Carbono orgánico en el suelo, del secuestro a las emisiones……………….35

1.3.1. El carbono orgánico, origen y fracciones…………………………….35

1.3.2. Factores que determinan el contenido de carbono orgánico en los suelos agrícolas……………………………………………………...38

1.3.2.1. Clima…………………………………………….……..39

1.3.2.2. Topografía……………………………………………....40

1.3.2.3. Material parental y propiedades del suelo……………………40

1.3.2.4. Vegetación y biota del suelo…………………………………41

1.3.2.5. Uso del suelo..……………………………………………42

1.3.3. Secuestro de carbono y prácticas agrícolas asociadas a este proceso…43

1.3.4. La estabilización de carbono orgánico, los diferentes almacenes del suelo…………………………………………………………………47

1.3.5. Principales pérdidas de carbono orgánico en suelos agrícolas……….51

1.3.6. Límites de la capacidad de carbono orgánico en el suelo, saturación y potencial……………………………………………………………..53

1.4. Tipología y manejo del olivar: estado del arte………………………………56

1.4.1. El olivar un cultivo mediterráneo de escala global…………………..56

1.4.2. Tipologías de los olivares andaluces…………………………………59

1.4.3. Principales manejos de los olivares andaluces……………………….63
1.4.3.1. Laboreo……………………………………………………63
1.4.3.2. No laboreo…………………………………………………...65
1.4.3.3. Cubiertas vegetales…………………………………………..67
1.4.4. La pérdida de suelo en los olivares de Andalucía……..……………..71
1.4.5. El olivar ecológico…………………………………………………...73
1.5. Referencias…………………………………………………………….....76

2. Hipótesis y objetivos……………………………………………………..102

3. Material y métodos. ……………………………………………………….107
3.1. Área de estudio……………………………………………………….109
3.2. Toma de muestras y preparación……………………………………..113
3.3. Métodos analíticos………………………………………………….....115
3.3.1. Densidad aparente……………………………………………………..115
3.3.2. Contenido en gravas…………………………………………………..115
3.3.3. Textura…………………………………………………………......115
3.3.4. pH…………………………………………………………….…116
3.3.5. Estabilidad estructural……………………………………………...117
3.3.6. Capacidad de retención de agua…………………………….....…118
3.3.7. Tasa de infiltración…………………………………………………119
3.3.8. Carbonatos…………………………………………………………….120
3.3.9. Carbono orgánico del suelo …………………………..…………120
3.3.10. Nitrógeno total……………………………………………………...121
3.4. Manejo de datos……………………………………………………...122
3.4.1. *Stock* de carbono orgánico……………………………………….122
3.4.2. *Stock* de nitrógeno total……………………………………….…122
3.4.3. Ratio de almacenamiento de C…………………………………..…122
3.4.4. Diámetro medio ponderado de los agregados (MWD) ……………123
3.4.5. Estimación de las pérdidas de suelo……………………………..…123
3.4.6. Índice de productividad del suelo……………………………..…124
3.5. Análisis estadístico…………………………………………………..…125
3.6. Referencias…………………………………………………………..…125

4. Resultados y discusion……………………………………………………..128

4.1. Long-term evaluation of the initiative 4‰ under different soil managements in Mediterranean olive groves………………………………………………….130

4.1.1. Introduction…………………………………………………..……133

4.1.2. Material and methods……………………………………………136

4.1.2.1. Site description and climatic parameters…………………...136

4.1.2.2. Experimental design……………………………………..139

4.1.2.3. Sampling and analisys…………………………….……..140

4.1.3. Results and discussion……………………………………………...142

4.1.3.1. General soil properties…………………………….……..142

4.1.3.2. Tillage and no-tillage effects on soil organic carbon concentration…………………………………………………....145

4.1.3.3. Tillage effects on total nitrogen concentration……………..150

4.1.3.4. Soil organic carbon and total nitrogen stock………………155

4.1.3.5. 4‰ initiative: the soil recarbonisation………………..……159

4.1.5 Conclusions………………………….……………………..163

4.1.6 References……….…………………………………………164

4.2 Effects of land management change on soil aggregates and organic carbon in Mediterranean olive groves…………………………………………………..177

4.2.1 Introduction……………………………………………………179

4.2.2 Material and methods…………………………………….…183

4.2.2.1 Study area……………………………………………….183

4.2.2.2 Experimental design and soil sampling……………….…...184

4.2.2.3 Analytical determinations…………………………………185

4.2.3 Results…………………………………………………………187

4.2.3.1 Soil aggregates-size distribution and mean weight diameter of aggregates……………………………………………………187

4.2.3.2 OC associated with aggregate-size fractions………………...189

4.2.3.3 Soil organic carbon stock within aggregate fractions………..191

4.2.4 Discussion…………………………………………………...194

4.2.4.1 Changes in aggregation distribution in soil profile…………..194

4.2.4.2 Distribution of OC in soil aggregates………………………..199

4.2.4.3 SOC stock within aggregate fractions……………………….200
4.2.5 Conclusions…………………………………………………….204
4.2.6 References…………………………………………………...206

4.3 Short-term effects of land management change linked to cover crop on soil organic carbon in Mediterranean olive grove hillsides……………………213
4.3.1 Introduction…………………………………………………….215
4.3.2 Material and methods…………………………………………..220
4.3.2.1 Study area……………………………………………………220
4.3.2.2 Experimental design…………………………………………222
4.3.2.3 Soil sampling, analytical methods and statistical analyses…..224
4.3.3 Results and discussion…………………………………………226
4.3.3.1 Basic soil properties…………………………………………..226
4.3.3.2 Organic matter, soil organic carbon, and stock. State of the art in the studied soils…………………………………..……231
4.3.3.3 Effects of conventional tillage on SOC, total N and C:N in the hillsides, baseline situation……………………………........236
4.3.3.4 Effects of no tillage on SOC, total N and C:N in the hillside, final stage research…………………………………………...238
4.3.3.5 Effects of land management change on SOC-S………………242
4.3.4 Conclusions…………………………………………………….246
4.3.5 References…………………………………………………...247

4.4 Soil productivity degradation in long-term eroded olive orchard under semiarid Mediterranean conditions……………………………………….....257
4.4.1 Introduction…………………………………………………….259
4.4.2 Material and methods…………………………………………..262
4.4.2.1 Site characterization and experimental design……………….262
4.4.2.2 Soil sampling and analysis……………………………………264
4.4.2.3 Soil loss estimation, Revised Universal Soil Loss Equation (RUSLE)…………………………………………………...265
4.4.2.4 Soil Productivity Index………………………………………266
4.4.3 Results……………………………..270
4.4.3.1 Pore size distribution and soil water retention………………..270

4.4.3.2 Infiltration……………………………………………...………..273
4.4.3.3 Soil erodibility and soil loss estimation…………..…………274
4.4.3.4 Soil Productivity Index.……………………………….…...275
4.4.4 Discussion……………………………………………………..….277
4.4.4.1 Changes in soil physical properties and water infiltration……277
4.4.4.2 Effect of soil management on soil erosion rates………………281
4.4.4.3 Soil productivity index changes under analyzed management practices…………………………………………………....283
4.4.5 Conclusions…………………………………………………….285
4.4.6 References…………………………………………………...286
5 Conclusiones……………………………………………………………299
6 Currículum científico……………………………………………...…304

Introducción

1. INTRODUCCIÓN.

1.1. Los suelos agrícolas ante el cambio climático.

1.1.1. El ciclo del carbono y su influencia en el cambio climático.

El proceso de cambio climático en La Tierra es una realidad constatable en el incremento de las temperaturas medias mundiales en 1ºC por encima de los niveles preindustriales (IPCC, 2018). Con el ritmo actual de incremento de temperaturas se prevé que este aumento sea superior y suponga 1,5 ºC en dos décadas con respecto a la situación preindustrial (IPCC, 2018). La Convención Marco de las Naciones Unidas sobre el Cambio Climático (CMNUCC, 1992) definió el proceso de cambio climático como "cambio de clima que se atribuye directa o indirectamente a la actividad humana que altera la composición de la atmósfera, y que se suma a la variabilidad natural del clima observada en períodos de tiempo comparables".

Como consecuencia de este incremento en las temperaturas globales, la frecuencia e intensidad de fenómenos meteorológicos extremos han aumentado (IPCC, 2018). De este modo, fenómenos como las olas de calor, las lluvias torrenciales o las sequías se han convertido en acontecimientos de mayor frecuencia, siendo especialmente relevantes en áreas de alta vulnerabilidad, como la Mediterránea, donde ya sufrían estos fenómenos y que se verán agravados debido a los incrementos en las emisiones de gases de efecto invernadero (GEIs) (EEA, 2017, 2019; Abd-Elmabod *et al*., 2020). De acuerdo con estas previsiones, el impacto que estos fenómenos tendrán en los sistemas agrícolas y la seguridad alimentaria será de gran relevancia (FAO, 2016).

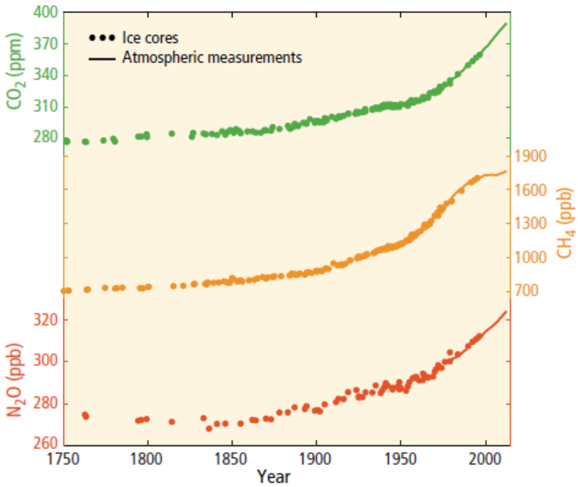


Figura 1. Promedio global de gases de efecto invernadero (Pachauri *et al*., 2014).

En esta evolución histórica de cambio climático que se viene constatando, y que se prevé que continúe, las emisiones de dióxido de carbono (CO_2), metano (CH_4) y óxido nitroso (N_2O) a la atmosfera (Figura 1) han sido señaladas como las principales responsables de este proceso (Huntingford y Mercado 2016; Jackson *et al*., 2018). De estas emisiones, las más abundantes en la atmósfera corresponden a las de CO_2 estando contabilizadas en 36,4 Gt para el año 2019 lo que supone un incremento de alrededor del 1% anual en la década previa (Global Carbon Budget, 2019; Friedlingstein *et al.*, 2020; Peters *et al.*, 2020). Sin embargo, para el año 2019 las emisiones se vieron reducidas ligeramente respecto a 2018 (37,1 Gt) y en el año 2020 con el impacto de la pandemia COVID-19 se estima un descenso de las emisiones hasta 34,1 Gt (Le Quéré *et al.*, 2020; Global Carbon Budget, 2020).

A escala global, los sectores económicos contribuyen de forma desigual al total de emisiones mundiales, de este modo los sectores de producción de electricidad y energético suponen el 25% de las emisiones; la agricultura, la silvicultura y otros usos de la tierra suponen el 24%; la industria, un 21%; el transporte, el 14%; otros sectores económicos suponen el 10% del total y las emisiones derivadas del uso residencial de los edificios e infraestructuras suponen un 6% (IPCC, 2014).

Es necesario destacar que los diferentes subsistemas de La Tierra, litosfera, biosfera, criosfera, hidrosfera y atmósfera interactúan continuamente a través de intercambios de GEIs, agua y energía. Estas interacciones hacen que los reservorios terrestres de carbono (C) puedan verse modificados mediante flujos que circulan de un subsistema a otro (Figura 2). El dinamismo en el flujo entre los diferentes reservorios planetarios provoca una continua circulación de C, que hacen que un subsistema pueda ser fuente o depósito de C, con lo que pequeños cambios pueden impactar fuertemente en los diferentes reservorios (Oertel *et al*., 2016). El suelo es uno de los grandes reservorios de C del planeta, se estima que los suelos albergan en el primer metro de profundidad 1505 Pg (1 Petagramo = 10^{15} g) que lo sitúan por encima de los reservorios en los subsistemas bióticos (560 Pg) y atmosféricos (867 Pg) mientras que los océanos contienen el mayor *pool* de C del planeta con 38.000 Pg (Batjes, 2016; Lal, 2018).

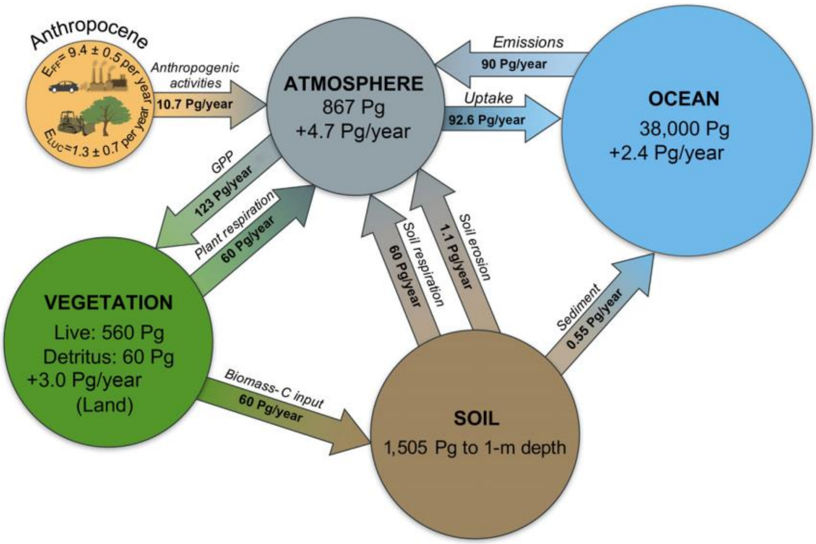


Figura 2. Ciclo global del carbono. Adaptado de Lal. (2018).

Por otro lado, las actividades antropogénicas tienen un fuerte impacto en las dinámicas globales de C y en los componentes del ecosistema (Pereira *et al.*, 2020). Las emisiones derivadas de la actividad humana han sido estimadas en 10,7 Pg por año para la década 2007-2016, de las que 9,4 Pg fueron derivadas de la combustión de combustibles fósiles y 1,3 Pg producidas por los cambios de uso de los suelos (Lal, 2018). La dimensión en los cambios que las emisiones de las actividades antropogénicas pueden provocar, ha llevado a que algunos autores defiendan que entramos en una nueva era denominada Antropoceno (Malhi, 2017; Laurence, 2019).

En este intercambio de C entre los diferentes subsistemas terrestres se estimó que, en la década referida, los suelos y otros componentes de la biosfera (vegetación y humedales) tuvieron capacidad para almacenar 3 Pg por año (Le Quéré *et al*., 2017). No obstante, el potencial de secuestro, almacenamiento y estabilización de C no es estático y puede variar dependiendo de las condiciones climáticas, el uso, las prácticas de manejo y las propiedades del suelo (Lal, 2003, 2008).

1.1.2 El papel de la agricultura como emisor y depósito de C.

Entre 1700 y la década de 1990, 1.135 billones de hectáreas (Bha) de bosques y áreas forestales y 0,669 Bha de sabanas, pastizales y estepas fueron convertidas en tierras de cultivo (Lal, 2010). Además, desde 1990 las tierras de cultivo a nivel mundial se han visto incrementadas considerablemente y se espera que se incrementen un 7% más hasta 2030 (FAO, 2015, 2016). En la actualidad las actividades agrícolas ocupan el 49% de la superficie de tierra libre de hielo del planeta, el 12% como tierras de cultivo y el 37% como pastos (Ledo *et al.*, 2020). Los sistemas agrícolas intensivos ejercen una importante presión sobre los recursos naturales, de modo que, su funcionamiento está actualmente en cuestión debido a que pueden causar la degradación del suelo (Pereira *et al*., 2020). Esto es especialmente relevante puesto que los suelos proporcionan el 99% de los alimentos mundiales (Kopittke *et al*., 2019) y se prevé que la población mundial se incremente en 2 billones de personas alcanzando los 9,7 billones en 2050 (Desa, 2019).

Asociada a la degradación de los suelos, se produce una pérdida de nutrientes y biodiversidad, además se contribuye a la disminución de la calidad y la escasez de agua y, en última instancia, a las emisiones de GEIs y de contaminantes atmosféricos (Abbas *et al*., 2017). Los suelos agrícolas contienen entre el 25% y 75% menos de carbono orgánico (OC) que los suelos homólogos no alterados o en ecosistemas naturales (Lal, 2004a). Los cambios de usos, deforestaciones o la propia actividad de cultivo del suelo repercuten en las reservas terrestres de C que de este modo se han visto alteradas por las actividades humanas con una estimación de pérdida de carbono orgánico del suelo (SOC) de entre 115-154 Gt C (Lal, 2018).

El impacto ambiental que generan las actividades agrícolas mediante la emisión de GEIs puede ser evaluado a partir de la huella de carbono. De acuerdo con Jaiswal y Agrawal (2019), en el sector agrícola pueden diferenciarse tres niveles según su procedencia que influyen en la huella de carbono del sector: las emisiones directas debido al uso de maquinaria y al manejo del suelo (Figura 3), emisiones indirectas relacionadas con la electricidad y, por último, emisiones indirectas debido a la fabricación y transporte de productos químicos y maquinaria agrícola. El total de las

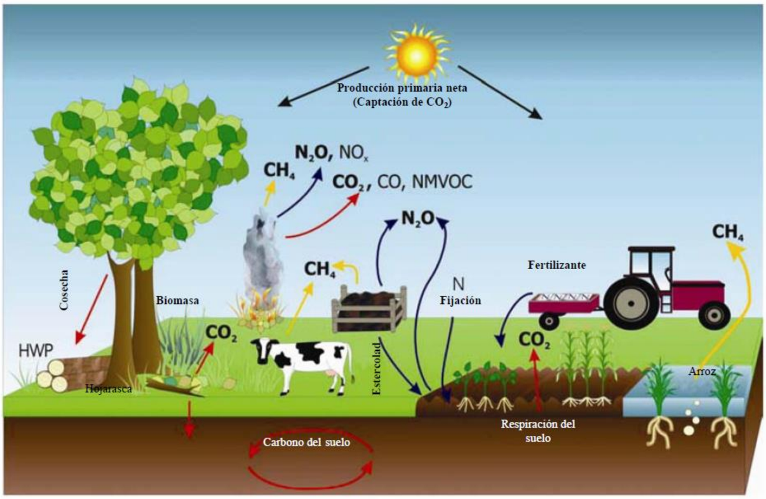


Figura 3. Principales fuentes de emisiones y secuestro de gases de efecto invernadero en agroecosistemas. IPCC. (2006).

emisiones del sector agrícola representan alrededor del 24% del CO_2, el 50% del CH_4 y el 70% de las emisiones antropogénicas de N_2O (Hutchinson *et al*., 2007). Las proyecciones muestran que las emisiones de GEIs agrícolas mundiales pueden aumentar hasta un 30% para 2050 (FAOSTAT, 2014).

No obstante, los agroecosistemas tienen un alto potencial para almacenar C, especialmente aquellos que han perdido gran parte de su *pool* de C a través de procesos de degradación, con lo que la restauración de estos reservorios podría ser una estrategia acertada en la lucha contra el cambio climático, la reducción de las emisiones a la atmosfera y el incremento de la calidad del suelo (Paustian *et al*., 2016; Zomer *et al*., 2017; Ma *et al*., 2018). Los niveles actuales de CO_2 atmosférico se reducirían entre un 5 y un 15% si las tierras de cultivo se transforman de fuente a sumidero de C (Lal, 2004b) aunque otras estimaciones son aún más generosas determinando una reducción de entre el 21-24% (Smith *et al*., 2014; Tubiello *et al*., 2015).

Las prácticas de manejo sostenible se han demostrado como fundamentales para alcanzar el potencial de secuestro de C de los suelos agrícolas (IPCC, 2019). De acuerdo con Lal (2018), la aplicación de prácticas de manejo sostenibles en los agroecosistemas implica la elección de prácticas específicas para cada contexto que (*1*) mantengan una cobertura continua del suelo durante todo el año con residuos de cultivos o cultivos de cobertura, (*2*) reemplacen los nutrientes extraídos con la producción a través de un manejo integrado de los nutrientes, (*3*) mejoren la estructura del suelo y los procesos rizosféricos y (*4*) mejoren la ecoeficiencia reduciendo las pérdidas por erosión, volatilización o lixiviación.

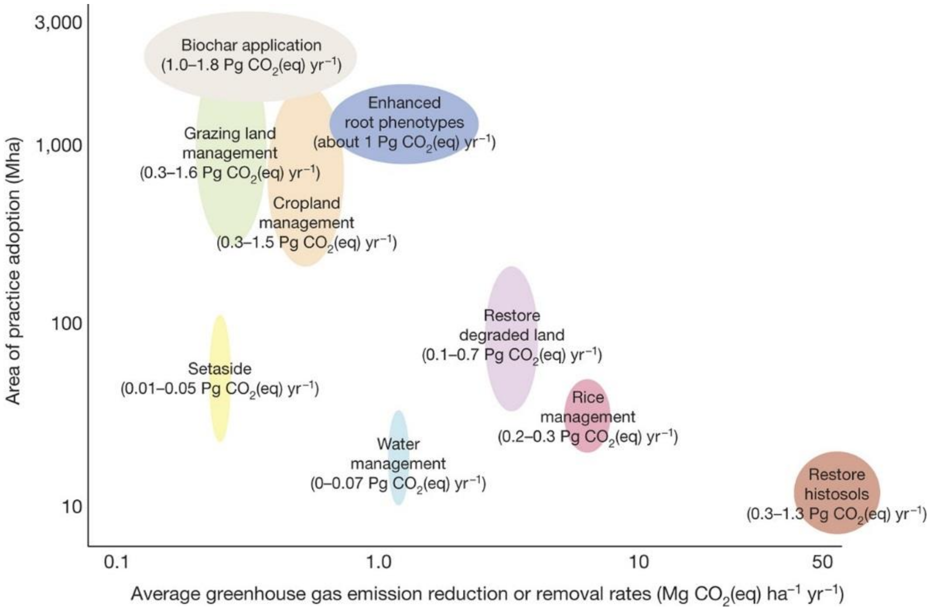


Figura 4. Prácticas de manejo y capacidad de mitigación (Paustian *et al*., 2016).

La instauración de prácticas de manejo sostenibles como la reducción del laboreo con mínimo o no laboreo, la rotación y diversificación de cultivos, el mantenimiento de cubiertas vegetales espontáneas, sembradas o inertes (mulching), la aplicación de biochar, la fertilización orgánica o una buena gestión de los residuos de las cosechas no solo son importantes para mitigar las emisiones de CO_2 y aumentar el ratio de secuestro de C en suelos agrícolas (Figura 4) sino que con el aumento de la materia orgánica del suelo estas prácticas mejoran la calidad del suelo incrementando su fertilidad (Oldfield *et al*., 2018), la capacidad de retener agua (Bogunovic *et al*., 2020; Morugán-Coronado *et al*., 2020) una mayor resistencia ante periodos prolongados de sequía (Zomer *et al*., 2017) y procesos erosivos (Bombino *et al*., 2020).

1.1.3. Iniciativa 4 por mil. El reto de los suelos agrícolas.

En los últimos años, con el incremento de las emisiones y concentraciones de CO_2 en la atmósfera, el papel de los suelos en el ciclo global del C ha sido cada vez más reconocido. Por iniciativa del Gobierno de Francia, a través de Stéphane Le Foll ministro de Agricultura (Le Foll, 2015), durante las negociaciones de la 21 Conferencia de las Partes de la Convención Marco de Naciones Unidas sobre el Cambio Climático COP21 (2015) en París, se introdujeron en la agenda de las políticas públicas el almacenamiento de carbono en los suelo agrícolas por primera vez desde el inicio de las reuniones de la COP en 1992, como herramientas para la mitigación del calentamiento global, que luego fueron refrendadas y ampliadas en la Cumbre de Marrakech 2016 (COP22).

La iniciativa 4‰ consiste en un plan de acción para incrementar el contenido de SOC en los primeros 40 cm de profundidad del suelo en un porcentaje del 0,4 por año. Este porcentaje se determina a partir de la relación entre el total anual de emisiones globales a partir de combustibles fósiles (8,9 Gt) y las existencias de SOC (2400 Gt) en los primeros 2 metros de suelos mundiales (Batjes, 2014) (Figura 5). Como resultado y como suplemento a una estrategia de reducción de las emisiones mundiales, el aumento del secuestro de SOC ha sido promovido por diferentes investigadores y encargados de la formulación de políticas como posible oportunidad adicional para contrarrestar en parte el aumento de las concentraciones atmosféricas de CO_2 (Smith *et al.*, 2016).

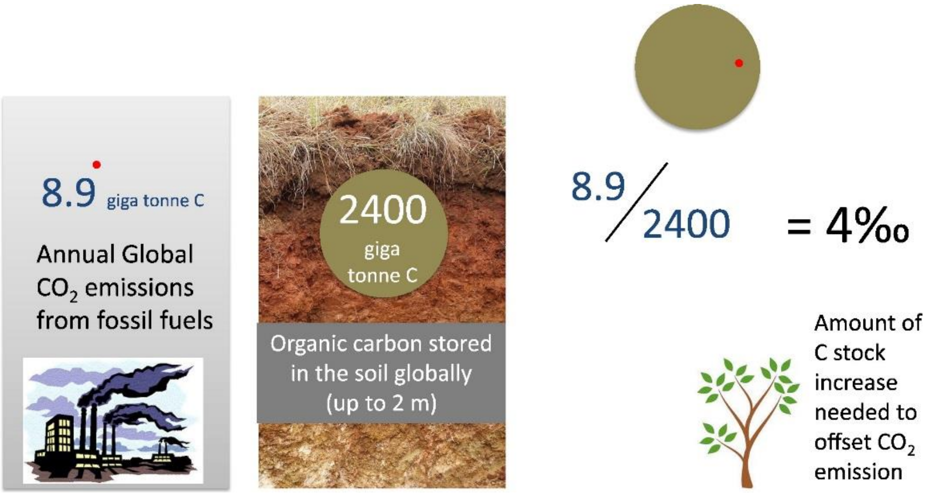


Figura 5. Esquema de la Iniciativa 4 por mil. Minasny *et al*. (2017).

Los cambios de este gran reservorio pueden afectar de manera significativa en las concentraciones de CO_2 en la atmósfera. La Iniciativa 4‰ se centra en los suelos agrícolas, por lo tanto, de acuerdo con Minasny *et al*. (2017) pueden lograrse altas tasas de secuestro de C en los primeros veinte años después de la aplicación de prácticas de manejo sostenibles 0,6 t/ha/año debido a que estos suelos de cultivo se caracterizan generalmente por tener bajos niveles de SOC.

Sin embargo, al objetivo que persigue la Iniciativa 4‰ se le han detectado importantes limitaciones como la profundidad de referencia en la iniciativa (40 cm) que descarta los horizontes profundos (Chabbi *et al.*, 2017), los incrementos de SOC a los que aspira la Iniciativa no son posibles en todas las situaciones agrícolas puesto que existe una gran variabilidad agrícola mundial (Chambers *et al*., 2016; Poulton *et al*., 2018), se basa en un incremento continuo durante 20 años que no tiene en cuenta factores adversos que pueden hacer reversible esta tendencia (Smith, 2016; Baveye *et al*., 2018) o que obvia otros gases que tienen gran repercusión en el incremento de las temperaturas globales como CH_4 o N_2O (Baveye *et al*., 2018).

Por otra parte, está ampliamente demostrado que un incremento de SOC mejora ciertas funciones del suelo, beneficiando así la productividad agrícola (Lal, 2016; Abbas *et al*., 2020). Además, es previsible que un aumento de SOC genere beneficios añadidos que ayuden a lograr varios de los objetivos de desarrollo sostenible (ODS) enmarcados dentro de la Agenda 2030 de la Organización de las Naciones Unidas (ONU) para el Desarrollo Sostenible (Figura 6). Principalmente los objetivos relacionados con la reducción del hambre (ODS 2), la pobreza extrema (ODS, 3), mejora de la protección del medio ambiente (ODS 6, 11, 12, 14, 15) y el clima global (ODS 13) (Bouma *et al*., 2019; Soussana *et al*., 2019). En particular, la Iniciativa puede tener la posibilidad de contribuir al ODS 15.3, combatiendo la desertificación y promoviendo la restauración de las tierras degradadas mediante el aumento de almacenamiento de SOC. Esto es especialmente importante en países subdesarrollados donde se espera que el cambio climático tenga importantes efectos en la degradación de los suelos y la reducción de las cosechas (Lal, 2019b, 2020a).

Figura 6. Objetivos de desarrollo sostenible. Organización de las Naciones Unidas.

1.1.4 La agricultura europea hacia la sostenibilidad ambiental.

Los sistemas agrícolas europeos contemporáneos son el resultado de la transformación agrícola bajo la influencia de las políticas y reformas agrícolas promovidas a lo largo del tiempo (Recanati *et al*., 2018). Las numerosas reformas de la Política Agrícola Común (PAC) han modelado y reorientado el sistema agrícola europeo, haciendo hincapié en sus aspectos multifuncionales (Garzon, 2006; Greer, 2017), en los que la necesidad de armonizar rentabilidad económica y preservación medioambiental se ha convertido en una prioridad (Gocht *et al*., 2017). Aunque existía en la Unión Europea (UE) una inquietud medioambiental, es a partir del año 2003 cuando en la reforma de la PAC estas cuestiones son abordadas con mayor determinación, a través de Requisitos Legales de Gestión y normas para el mantenimiento de las explotaciones en Buenas Condiciones Agrarias y Medioambientales, la denominada condicionalidad, recogida en el Reglamento UE nº 1306/2013. Esta visión continuó con la reforma de 2013 con la que se incrementaban los apoyos directos a los productores (EC, 2013), sin embargo, las medidas “greening” han demostrado tener un impacto limitado en cuanto a las mejoras ambientales de las áreas agrícolas europeas (Alons, 2017; Angileri *et al.*, 2017; Hristov, *et al.*, 2020). La nueva propuesta financiera y legislativa de la PAC (2021-2027) fue publicada por la Comisión Europea en 2018 (EC, 2018), en ella se propone ajustar las ayudas a las mejores prácticas de manejo ante los impactos del cambio climático. Esta propuesta ha sido aprobada por el Parlamento Europeo y los estados miembros de la UE en noviembre de 2020 y constará de un periodo transitorio durante los años 2021-2022.

Con el Pacto Verde Europeo, lanzado en 2019 (EC, 2019), se pretende un renovado impulso en esta dirección con un plan de acción que pretende la neutralidad climática en la UE para 2050 mediante el impulso del uso eficiente de los recursos, la restauración de la biodiversidad y la reducción de la contaminación. En esta estrategia los suelos tienen un papel central estando presente en diferentes ámbitos de actuación (Figura 7) como los de biodiversidad (BDS, 2020), “*farm to fork*” (F2F, 2020) y de neutralidad climática (EU Climate Law, 2020). La implantación de prácticas de manejo sostenibles será de vital importancia para conseguir los objetivos del pacto verde europeo (Wiesmeier *et al.*, 2020) estando incluidas medidas específicas como la reducción de fertilizantes o pesticidas en los planes de acción de las diferentes áreas del plan (Montarella y Panagos, 2020).

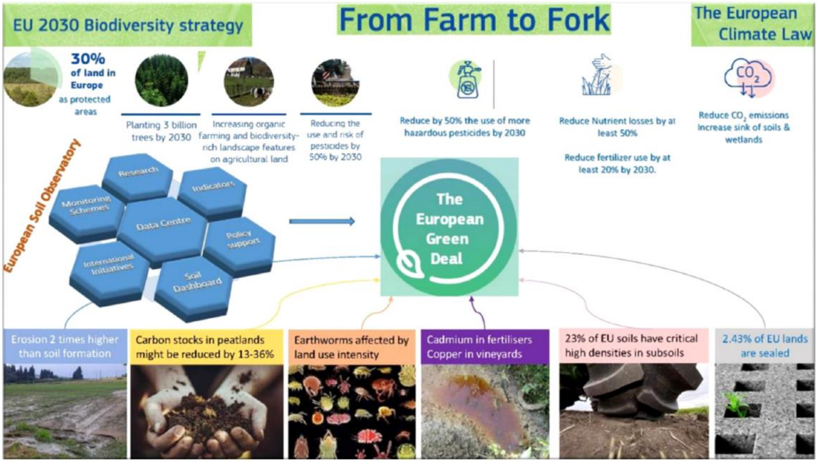


Figura 7. Los suelos en el Pacto verde europeo. Montarela y Panagos, (2020).

En definitiva, desde las instituciones europeas se reconoce el papel central de los suelos y se están promoviendo dinámicas orientadas a una modificación de los manejos agrícolas hacia agroecosistemas más sostenibles dando cabida a otras realidades y favoreciendo nuevas oportunidades (De Bernardi y Azucar, 2020; Bouma, 2020). El interés por emprender acciones que impulsen nuevos modelos de agroecosistemas, teniendo en cuenta su carácter multifuncional para la puesta en valor de funciones del mismo, tales como la provisión de productos saludables y de calidad, el mantenimiento de la población y de sistemas locales de producción, la contribución del cultivo a la mitigación de la erosión, la lucha contra el cambio climático, la eficiencia en el uso de los recursos hídricos, la preservación de paisajes agrarios tradicionales y el mantenimiento de la diversidad biológica (Veerman *et al*., 2020).

1.2. La materia orgánica del suelo, la esencia del agroecosistema.

1.2.1 La materia orgánica del suelo, un elemento complejo.

La materia orgánica del suelo (SOM) es un conglomerado de sustancias biogeoquímicas formadas principalmente por restos vegetales, animales y exudados, que son transformados por microorganismos y descompuestos bajo diferentes condiciones ambientales (temperatura, y humedad) (Stevenson, 1994). La SOM es una fuente de energía y nutrientes para los organismos del suelo, contiene elementos esenciales para las plantas, como carbono, nitrógeno, fósforo, magnesio, calcio, azufre y micronutrientes (Graetz, 1997), pudiendo estar formada por diversos compuestos en diferentes grados de descomposición o humificación (Paul, 2014) y distribuida de forma desigual a lo largo del perfil del suelo.

En la SOM puede diferenciarse una fracción lábil, de fácil asimilación y disponibilidad por los organismos del suelo, esta fracción mantiene las propiedades químicas del material original y reside en el suelo por espacios cortos de tiempo (Abdelrahman *et al.*, 2020). Dentro de la fracción lábil pueden distinguirse proteínas, aminoácidos o carbohidratos que son esenciales en la fertilidad del suelo. Por otro lado, se encuentra la fracción húmica que tiene una mayor estabilidad (Milori *et al.*, 2002) y representa la mayor parte de la SOM (Simpson *et al.*, 2007). Está formada por tres fracciones diferentes, ácidos fúlvicos, ácidos húmicos y huminas, que se dividen en base a su solubilidad bajo condiciones ácidas o alcalinas (Paul *et al.*, 2001; Gao *et al.*, 2018). La fracción húmica es resistente de la descomposición microbiana pudiendo persistir en el suelo durante largos periodos de tiempo.

1.2.2. Fracciones de la materia orgánica.

En la SOM se pueden diferenciar fracciones según su tamaño (Figura 8), el análisis de las diferentes fracciones es útil para determinar y evaluar las diversas estrategias de manejo de los suelos y los impactos a corto y largo plazo (Devine *et al*., 2014). Las fracciones de SOM del suelo se pueden caracterizar mediante la dispersión de sus partículas y un sencillo fraccionamiento físico, existiendo diferentes metodologías para ello (Cambardella y Elliot 1992; Franzlubbers y Arshad, 1997). Las fracciones resultantes del fraccionamiento generalmente se clasifican en tres grandes grupos: materia orgánica particulada gruesa >250 µm (cPOM), materia orgánica particulada fina 53–250 µm (fPOM), y la materia orgánica asociada a la fracción mineral <53 µm (MAOM). Por lo general, POM (fracciones superiores a 53 µm) se compone en gran medida por material con bajo grado de descomposición, mientras que MAOM está formado por moléculas o fragmentos microscópicos de material orgánico que se han lixiviado del material vegetal o que han sido químicamente transformados por la biota del suelo (Lavallee *et al*., 2020).

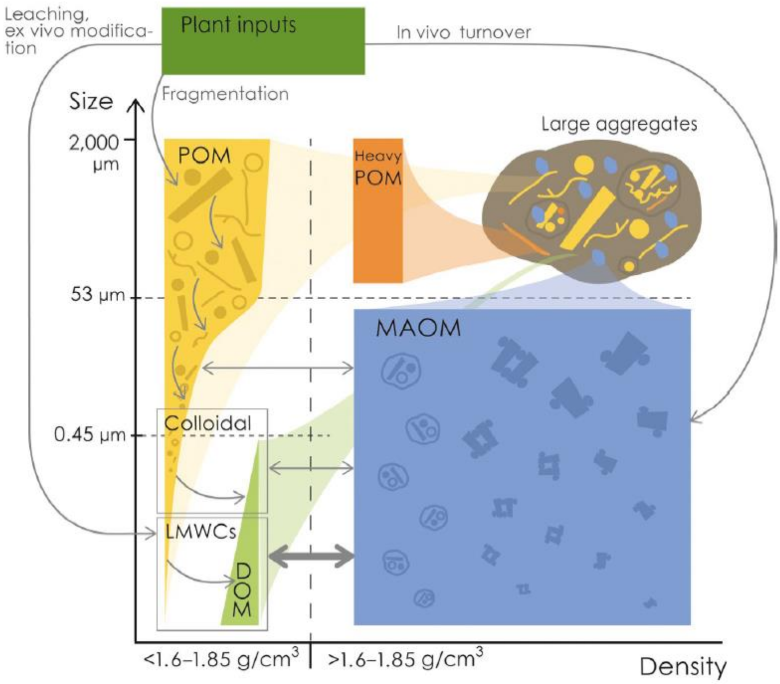


Figura 8. Fracciones de la materia orgánica. Materia orgánica particulada (POC), materia orgánica asociada a la fracción mineral (MAOM) materia orgánica disuelta (DOM) y componentes moleculares (LMWCs). Adaptado de Lavalee *et al*. (2020).

El análisis de POM y MAOM no permite considerar explícitamente los agregados del suelo. Este procedimiento implica que los agregados de mayor tamaño (>53 µm) se han dispersado antes del fraccionamiento físico y, por lo tanto, se centra en los componentes "estables" que permanecen intactos después de dicha dispersión (Lavallee *et al*., 2020). Aunque, tras el proceso de dispersión, se mantienen agregados de partículas orgánicas e inorgánicas de varios tamaños pese a la gran disrupción de los agregados (Chenu y Plante, 2006; Sollins *et al*., 2009; Totsche *et al*., 2018). Estos agregados finos y estables (<53 µm) se incluyen en la fracción MAOM. Las implicaciones de una gran perturbación de la agregación se examinan más adelante (apartado 1.3.4).

1.2.3 La materia orgánica y su rol en la provisión de servicios ecosistémicos en los suelos agrícolas.

La SOM representa un pequeño porcentaje de la masa del suelo, a pesar de ello, es considerada como un elemento clave dentro del agroecosistema y un indicador fundamental en la evaluación de la calidad de los suelos (Jarecki y Lal, 2005), tanto por su interés agronómico como medioambiental (FAO, 2017; Khalid *et al*., 2019). En la mayoría de los sistemas agrícolas bajo prácticas de manejo convencionales el contenido de SOM sigue una tendencia descendente en relación al tiempo de cultivo (Garratt *et al*., 2018), mostrando niveles bajos en comparación con suelos en espacios naturales de similares características. Sin embargo, el porcentaje de SOM presente en el suelo determina en gran medida sus propiedades físicas, químicas y biológicas, en consecuencia, condiciona la provisión de servicios ecosistémicos por parte de los suelos agrícolas (Figura 9) (Dominati *et al*., 2010; Reynaldo *et al*., 2012; Campbell and Paustian, 2015; Baveye *et al*., 2016).

Los servicios ecosistémicos han sido definidos como “los beneficios que la sociedad obtiene de los ecosistemas” (MEA, 2005), en la provisión de estos servicios por parte de los suelos agrícolas el contenido de SOM influye en aspectos elementales como:

I. La SOM proporciona nutrientes de diversa índole para el desarrollo de los cultivos (Ghaley *et al*., 2018), con lo que participa en la formación de las plantas que luego son cosechadas para fines diversos (alimentos, fibras, construcción, medicinas) (Oldfield *et al*., 2019).

II. Incrementa la capacidad de intercambio catiónico (CIC) (Ramos *et al*., 2018), con lo que, aumenta la disponibilidad de nutrientes para las plantas y reduce la lixiviación. Por lo tanto, retiene contaminantes del suelo (Qi *et al*., 2017) y previene la posible contaminación de los ecosistemas acuáticos o el agua de consumo humano.

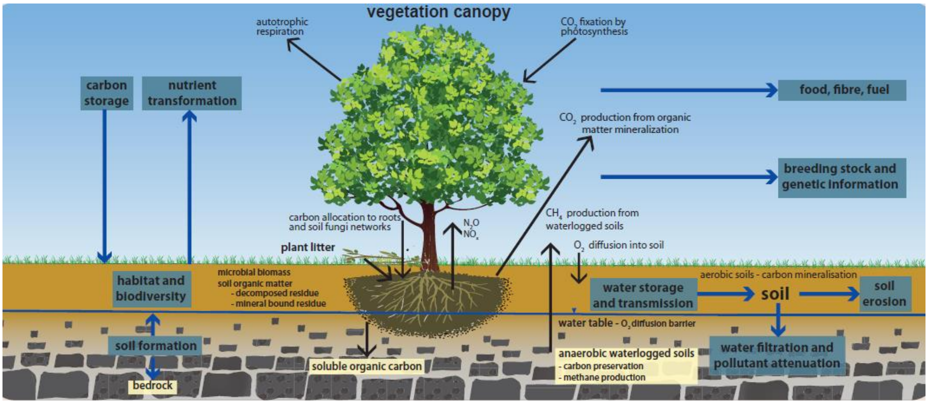


Figura 9. Servicios ecosistémicos asociados a la materia orgánica de los suelos. Adaptado de Reynaldo *et al*. (2012).

III. Con el incremento de SOM se reduce la densidad aparente del suelo (BD), incrementando el tamaño de los poros y la permeabilidad (Bauer and Black, 1992; Warkentin, 2008). Además, la capacidad de retención de agua aumenta generalmente con valores altos de SOM (Haynes and Naidu, 1998), con lo que se favorece el almacenamiento de agua en el suelo (Rakic *et al*., 2009).

IV. La SOM actúa en la regulación de avenidas e inundaciones, son numerosos los estudios que han demostrado, bajo diferentes tipologías de suelos, que un incremento en la SOM aumenta la infiltración, reduciendo las tasas de erosión y escorrentía en los suelos agrícolas (Guerra, 1994; Kuhn, 2007; Obalum *et al*., 2017; Ouyang *et al*., 2018).

V. La SOM fomenta la biodiversidad y la actividad microbiana puesto que es una fuente de energía y alimento para los organismos del suelo (Bagyaraj *et al*., 2016). La actividad y diversidad de la biota del suelo tiene gran influencia en la estructura del suelo, el ciclo de nutrientes y en el control biológico de plagas, aspectos que influyen en otros procesos como la productividad de los cultivos (Barrios, 2007).

VI. El rol que juega la cantidad de SOM en los flujos de GEIs de los agroecosistemas es de gran relevancia (Pries *et al*., 2017), participando en la regulación de las emisiones al actuar como sumidero de C. Por lo tanto, influye en la calidad del aire y actúa como regulador climático (Francaviglia *et al*., 2018).

1.3. Carbono orgánico en el suelo, del secuestro a las emisiones.

1.3.1. El carbono orgánico del suelo, origen y fracciones.

El SOC es el principal componente de la SOM (Lefevre *et al*., 2017), se estima que el 50%, de la SOM está formado por C (Pribyl, 2010). Aunque una parte del C del suelo proviene de minerales, la gran mayoría tiene su origen a partir de las plantas. A medida que las plantas crecen y mueren dejan componentes orgánicos que contienen C de tamaño y composición variables. Bajo condiciones ambientales adecuadas, principalmente de temperatura y humedad, la biota del suelo metaboliza estos compuestos orgánicos, incorporando parte del C en el suelo a través de nuevos compuestos químicos y dentro de su propia biomasa, mientras que el resto es devuelto a la atmósfera como CO_2 o se excreta de nuevo en el suelo (Kane, 2015; Wiesmeier *et al*., 2019).

De acuerdo con el tamaño y la fuente, el SOC se puede distinguir en diversas fracciones, representado todas juntas el carbono orgánico total del suelo (TOC) y que, por separado, pueden responder de modo diferente ante distintos impactos producidos en los suelos (Figura 10). El carbono orgánico particulado (POC) es el carbono presente en la fracción >53 μm. Las mayores concentraciones de POC se encuentran en la capa superficial de suelo debido a que es un material orgánico poco transformado. El contenido en POC influye directamente en la comunidad de microorganismos del suelo (Fierer *et al*., 2009) debido a que, por su alto porcentaje de C, una amplia variedad de hongos y bacterias encuentra en esta fracción una fuente de alimento y energía (Eskelinen *et al*., 2009). El contenido de POC refleja las modificaciones en el suelo, respondiendo en espacios cortos de tiempo a alteraciones ambientales o cambios inducidos por el manejo (Ladoni *et al*., 2015; Xue *et al*., 2018). Esta fracción suele representar entre el 8 y el 25% del TOC (Chan *et al*., 2007), en ella el C se encuentra en un paso intermedio entre los restos vegetales y el almacenamiento en el suelo (Borges *et al*., 2018).

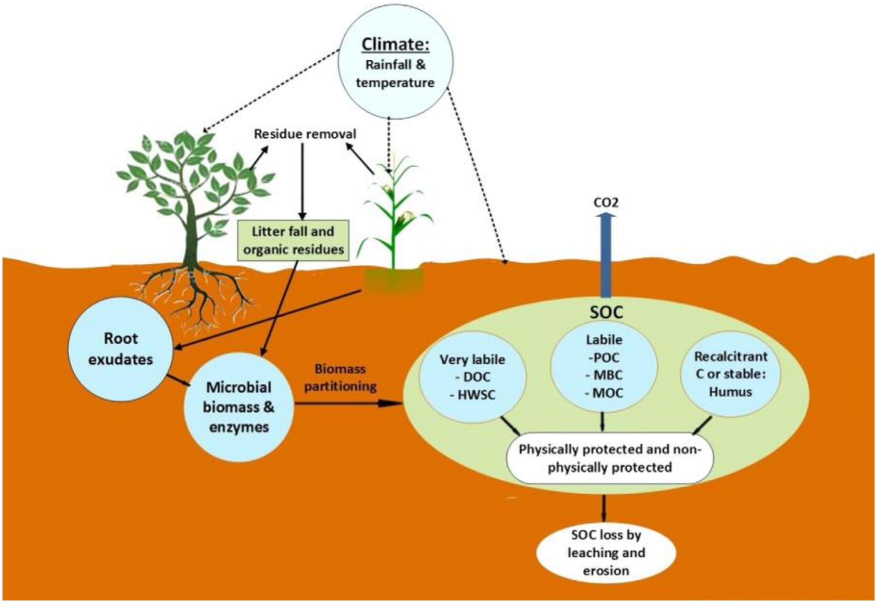


Figura 10. Dinámica de las fracciones de SOC. Adaptado de Ramesh *et al.* (2019).

Por su parte, el carbono orgánico asociado a la fracción mineral (MOC) es la fracción < 53 µm. Esta fracción es menos sensible que el POC a los cambios de manejo y tiene un papel importante como agente de agregación debido a su baja densidad (Cambardella y Elliot, 1994). Además, MOC muestra una sólida estabilidad del C y un incremento en su proporción en el suelo indica la descomposición y estabilización de POC (Plante *et al.*, 2010; Baiano y Morra, 2017).

De acuerdo con Ramesh *et al*. (2019) el carbono orgánico disuelto (DOC) puede considerarse como “un conjunto de moléculas de carbono orgánico de diversos tamaños, composiciones y estructuras que pasa a través de un filtro 0,45µm”. El DOC se origina a partir de múltiples fuentes como los desechos de las plantas, los exudados de las raíces, el humus del suelo o la biomasa microbiana (Bolan *et al*., 2004). El movimiento de DOC a lo largo del perfil es un importante proceso de transporte de C en el suelo desde superficie a horizontes profundos (Neff y Asner, 2001), siendo propuesto como un indicador de C disponible para microorganismos (Kalbitz *et al*., 2000).

Por su parte, el carbono orgánico de la biomasa microbiana (MBC) representa la fracción viva de SOC en el suelo (Iglesias, 2008). El análisis de la MBC puede ser utilizado como una estimación de la actividad biológica de los suelos y un indicador de estrés y perturbación de los suelos agrícolas (Zhang *et al*., 2017).

Por último, el carbono orgánico extraíble (WEOC) es una fuente de energía de rápida absorción por los microorganismos. Este carbono lábil es altamente degradable, estando disponible en el suelo durante espacios cortos de tiempo. En su composición son habituales sustancias como proteínas, aminoácidos y azúcares como la glucosa. El WEOC suele incrementar su proporción exponencialmente en el suelo con la incorporación de fertilizantes orgánicos (Mitchell *et al*., 2015) y es un indicador de la calidad de la materia orgánica (Hamkalo y Bedernichek, 2014).

1.3.2 Factores que determinan la presencia de carbono orgánico en los suelos agrícolas.

En los suelos agrícolas influyen un gran número de variables que determinan la presencia de SOC. De este modo, el contenido de SOC depende de factores que se interrelacionan entre sí como el clima, la topografía, el material parental, las propiedades del suelo, la vegetación y la biota o los usos del suelo.

1.3.2.1 Clima.

Las condiciones climáticas de un lugar se han demostrado como determinantes en el contenido de SOC de los suelos (Viscarra-Rossel *et al.*, 2014; Muñoz-Rojas *et al.*, 2017). Las precipitaciones y las temperaturas son factores esenciales para la entrada de C en el suelo y la descomposición de SOM. Las precipitaciones marcan en gran medida el desarrollo de la vegetación y la generación de biomasa que sirve como fuente de entrada de C en el suelo (Hobley *et al.*, 2016). Por otra parte, las temperaturas tienen una gran influencia sobre el desarrollo de la actividad microbiana y, por lo tanto, en la transformación de SOC (Anderson y Nilson, 2001).

Aunque en estas relaciones entre factores climáticos y SOC existen multitud de variables con influencia en los diferentes procesos de almacenamiento, estabilización y pérdida de SOC, a escala global los niveles de SOC son superiores en áreas frías y húmedas que en zonas con climas secos y cálidos (Figura 11) (Minasny *et al.*, 2017; Koven *et al.*, 2017). Incluso las precipitaciones medias anuales y las temperaturas medias anuales han sido tomadas como indicadores de contenido de SOC en estudios a gran escala (Jobbagy and Jackson, 2000).

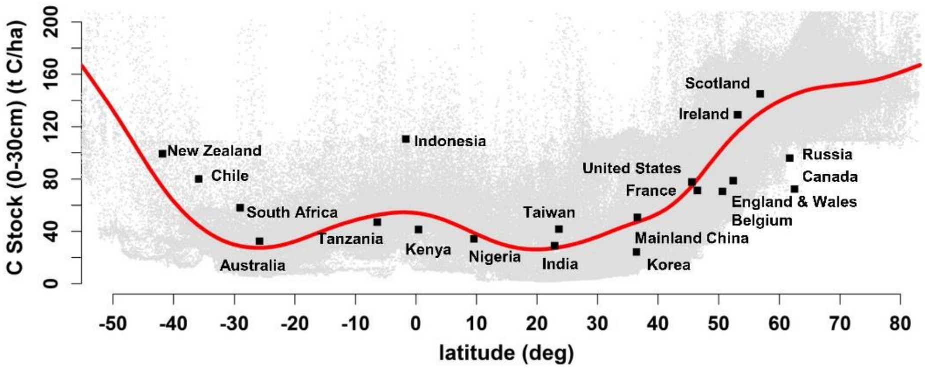


Figura 11. C *Stokc* en los primeros 30 cm de suelo en diferentes latitudes. Adaptado de Minasny *et al*. (2017).

1.3.2.2 Topografía.

Las características y formas que presenta el relieve han sido evidenciadas como un factor importante en el contenido de SOC de los suelos (Fernández-Romero *et al.*, 2014; Cardinael *et al.*, 2017) debido a su influencia en los procesos erosivos, disponibilidad de agua y el crecimiento de los cultivos (Minasny *et al*., 2013; Fissore *et al*., 2017). Áreas de baja pendiente o cóncavas favorecen la acumulación de agua y humedad, con ello se favorece el desarrollo de vegetación y el incremento de la producción primaria con lo que las entradas y el contenido de SOC se incrementa (Figura 12) (Bochet, 2015). Pero también la humedad del suelo puede favorecer el desarrollo de actividad microbiológica con lo que se fomenta la descomposición de la SOM y las salidas de SOC (Scowcroft *et al*., 2008). Por lo tanto, la humedad del suelo se ha determinado como un factor decisivo en la distribución de SOC (Mayes *et al*., 2014).

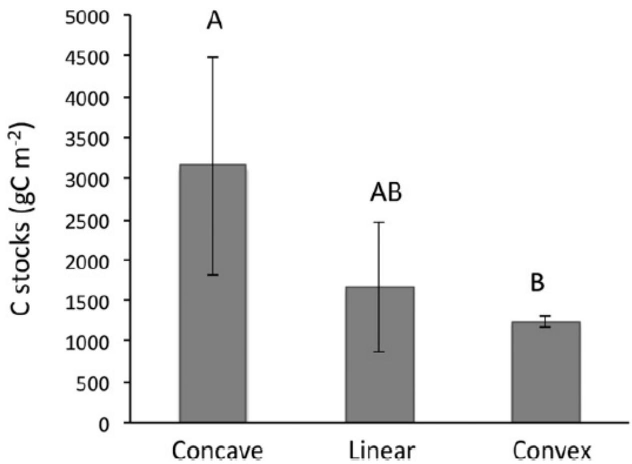


Figura 12. Contenido de SOC en diferentes topografías bajo clima Mediterráneo. Adaptado de Fissore *et al*. (2017).

Las características topográficas del terreno (posición en la ladera, porcentaje de pendiente) tienen gran influencia en el microclima local, especialmente cuando no existe una alta uniformidad, con lo que la distribución de C a escala local puede verse afectada por estas alteraciones (Parras-Alcántara *et al*., 2015; González-Rosado *et al*., 2020b).

1.3.2.3 Material parental y propiedades del suelo.

El efecto del material parental sobre el contenido del SOC se ha puesto de manifiesto en diversos estudios (Xiong *et al*., 2014; Angst *et al*., 2018). El material parental influye en el contenido de SOC en función de su textura, mineralogía o fertilidad (Wang *et al.*, 2008; Wiessmeier *et al*., 2014; Dwivedi *et al*., 2017).

El material parental está altamente relacionado con el tipo de suelo, y la tipología del suelo es un factor de gran importancia en la concentración de SOC tanto en los primeros centímetros del suelo como en los horizontes profundos (López-Fando y Pardo, 2009; Vasques *et al*., 2010; Hobley *et al*., 2015). La composición textural del suelo es probablemente una de las propiedades con una relación más estrecha con el contenido en SOC, mostrando en numerosas investigaciones una alta correlación entre el contenido de SOC y el porcentaje de la fracción de arcillas (Zinn *et al*., 2007; Martin *et al*., 2011) y siendo uno de los indicadores más utilizados en las estimaciones de distribución espacial de SOC (Kunkel *et al*., 2011; Feng *et al*., 2013).

1.3.2.4 Vegetación y biota del suelo.

El desarrollo de la vegetación a través de la biomasa afecta a la cantidad de entrada de SOC en los suelos (Ren *et al*., 2012), también el tipo y composición de la vegetación tiene efecto sobre las propiedades químicas de la SOM (Rumpel *et al*., 2009; Armas-Herrera *et al*., 2016). Además, los sistemas de cultivo dominados por vegetación con sistemas radiculares profundos, como los cultivos leñosos, promueven el almacenamiento de SOC en los horizontes profundos, ya que se ha comprobado que la retención del C derivado de las raíces de las plantas puede ser incluso superior al que aporta los restos vegetales en la capa superficial (Kätterer *et al*., 2011).

Por otra parte, otros estudios han encontrado evidencias de que la acumulación de SOC está impulsada por diversas comunidades microbianas a través de procesos de mineralización y estabilización de la SOM (Hoorman y Islam, 2010; Kallenbach *et al*., 2016). La estimulación de la actividad microbiana en los suelos mediante técnicas de manejo apropiadas se ha propuesto como una opción para reducir las pérdidas de SOC (Jastrow *et al*., 1998; Liang *et al*., 2017). Conjuntamente, la fauna del suelo también juega un rol importante en los procesos estabilización de SOC, de este modo, lombrices, ácaros, ciempiés o gusanos afectan a la estructura del suelo aumentando la macroporosidad y fomentando los procesos de agregación (Mora *et al*., 2005; Fonte *et al*., 2009; Falco y Coviella, 2016).

1.3.2.6 Uso del suelo.

El uso del suelo es uno de los factores más importantes en la evolución del contenido de SOC (Lozano-García *et al*., 2020). Los suelos bajo uso forestal o pastizal presentan valores superiores de SOC que los suelos dedicados al manejo agrícola. Los cambios en el uso del suelo han demostrado que conllevan un declive en el contenido de SOC cuando los suelos pasan de estar bajo usos forestales o de pastizal a uso cultivado, se estima que estas pérdidas pueden estar entre el 30 y 80 % del SOC (Kasel y Bennett, 2007; Wei *et al*., 2014). Sin embargo, los cambios pueden producirse en la dirección contraria, es decir un incremento en el contenido de SOC cuando los suelos dedicados al cultivo pasan al uso forestal o pastizal (Schulp and Veldkamp, 2008) e incluso cuando pasan a convertirse en tierras abandonadas (Choudhury *et al*., 2014; Novara *et al*., 2017).

Además, se ha demostrado ampliamente que los procesos de deforestación o cambios de usos del suelo de forestal a terreno cultivado no solo conllevan la reducción de *stock* de SOC (SOC-S) sino que también suponen la reducción de nutrientes y de la fertilidad a través de procesos de erosión, reducción en la cantidad de material orgánico añadido al suelo y la alteración de la estructura del suelo (Ribeiro Filho *et al*., 2015; De Blécourt *et al*., 2019). Aunque estos cambios puede que no afecten en los primeros años a la productividad del cultivo debido a la acumulación previa de material orgánico, un manejo agrícola intensivo puede esquilmar estas reservas con el paso del tiempo (Poeplau *et al*., 2011).

1.3.3. Secuestro de carbono y prácticas de manejo.

Desde hace más de cuatro décadas existe la inquietud por tomar CO_2 de la atmósfera y almacenarlo en el suelo. Freeman Dyson (1977) comentaba "la creación de bancos de carbono para acumular reservas de carbono en forma humus". En la actualidad y de acuerdo con Olson *et al.* (2014) el secuestro de carbono se puede definir como "el proceso de transferir CO_2 de la atmósfera al suelo, a través de plantas, residuos de plantas y otros sólidos orgánicos que se almacenan o retienen como parte de la materia orgánica del suelo (humus). El tiempo de retención del carbono secuestrado en el suelo (almacén terrestre) puede variar desde el almacenamiento a corto plazo (no se libera inmediatamente a la atmósfera) hasta el almacenamiento a largo plazo (milenios)". Para Powlson *et al.* (2011) el termino secuestro debería usarse exclusivamente cuando se produce una transferencia neta de C desde la atmósfera al suelo y se contribuye a la mitigación del cambio climático y no cuando se produce un intercambio de C entre subsistemas.

Pero es importante destacar que a través del secuestro de carbono y el incremento de SOC en los suelos no solo se mitiga el cambio climático, sino que se pueden restaurar suelos agrícolas degradados (Chabbi *et al.*, 2017).

El secuestro de SOC tiene limitaciones espaciales y temporales, siendo un proceso reversible (Paustian *et al.*, 2016). El SOC-S en los suelos agrícolas es relativamente estable, acercándose a un equilibrio a largo plazo bajo condiciones ambientales poco variables, donde las entradas de SOC y la degradación de materia orgánica son constantes (Wiesmeier *et al.*, 2020). Este equilibrio en el SOC-S se puede transformar hacia un balance positivo o negativo según incrementen o disminuyan las entradas y salidas de SOC del suelo, por lo tanto, a través de prácticas de manejo y cambios de uso se puede influir en este balance de carbono alcanzando un nuevo equilibrio (Figura 13) (Rumpel *et al.*, 2020).

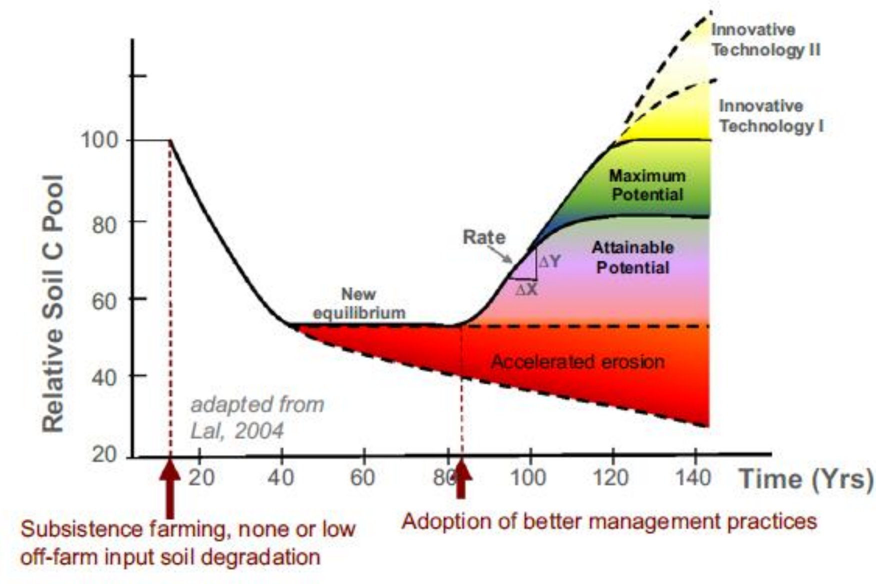


Figura 13. Trayectoria del contenido SOC en diferentes situaciones. Adaptado de Lal (2004b) y Rumpel *et al*. (2020).

Para lograr un incremento efectivo en el SOC-S en los suelos agrícolas, las prácticas de manejo aplicadas son fundamentales. Gracias a numerosas investigaciones, una serie de prácticas de manejo (Best Managament Practices) se han demostrado como válidas en el incremento de SOC de los suelos agrícolas, entre ellas la labranza cero o de conservación (Peigné *et al*., 2018), la aplicación de insumos orgánicos (estiércoles o compost) (Diacono y Montemurro, 2011), la rotación de cultivos (Jian *et al*., 2020), el mantenimiento de cubiertas vegetales (Kaye y Quemada, 2017) y restos de cosecha (Sarker *et al*., 2019), la conversión de cultivos anuales a perennes (Ledo *et al*., 2020) o la agricultura orgánica (Eyhorn *et al*., 2019).

En general este conjunto de prácticas de manejo agrícola tiene en común una serie de aspectos (Figura 14) que conducen hacia un incremento en el SOC-S en los suelos agrícolas, pudiendo englobarse en:

- Reducción de la alteración física del suelo (labranza) para evitar desestructuración del suelo y rotura de agregados.
- Incremento de la diversidad y la abundancia microbiana del suelo.
- Aumento de la biomasa orgánica que se incorpora al suelo.
- Mantenimiento de la cobertura del suelo a lo largo del año.

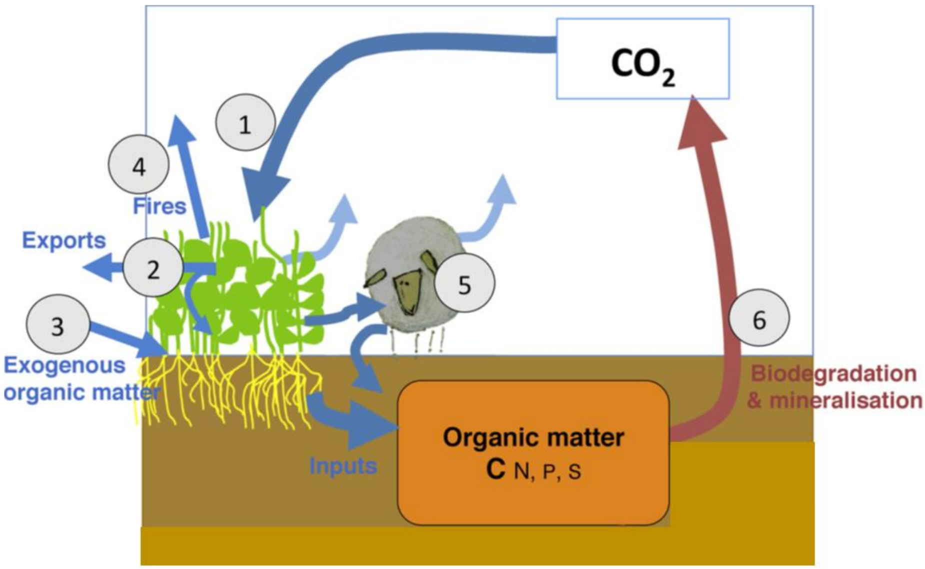


Figura 14. Fuentes asociadas a las prácticas agrícolas que pueden influir en el contenido de SOC: (1) aumento de la producción primaria (2) incremento del retorno de la biomasa al suelo, (3) aportación de residuos orgánicos al suelo, (4) evitar las quemas, (5) gestión de pastizales y cubiertas, (6) disminución tasas de biodegradación y mineralización (reducción de labranza). Adaptado de Chenu *et al*. (2019).

1.3.4. La estabilización del carbono orgánico, los diferentes almacenes del suelo.

De acuerdo con Chenu *et al*. (2019), el almacenamiento de carbono se define como “el contenido en las reservas de SOC a lo largo del tiempo en los suelos en un área determinada y a una profundidad conocida, no siendo necesariamente asociado a una eliminación neta de CO_2 de la atmósfera”.

El SOC puede mantenerse en el suelo como reservorio en diferentes *pools*. La estabilización de SOC a través de procesos de agregación de las partículas del suelo es un proceso fundamental para entender el funcionamiento de las dinámicas de C en el suelo. Los agregados son partículas orgánicas y minerales unidas entre sí con mayor resistencia que partículas adyacentes (Chevallier, 2011). De acuerdo con Six *et al*. (2000) la SOM es el principal aglutinante en la constitución de los agregados, que pueden seguir un proceso de formación o degradación dependiendo de las perturbaciones sufridas por el suelo (Figura 15).

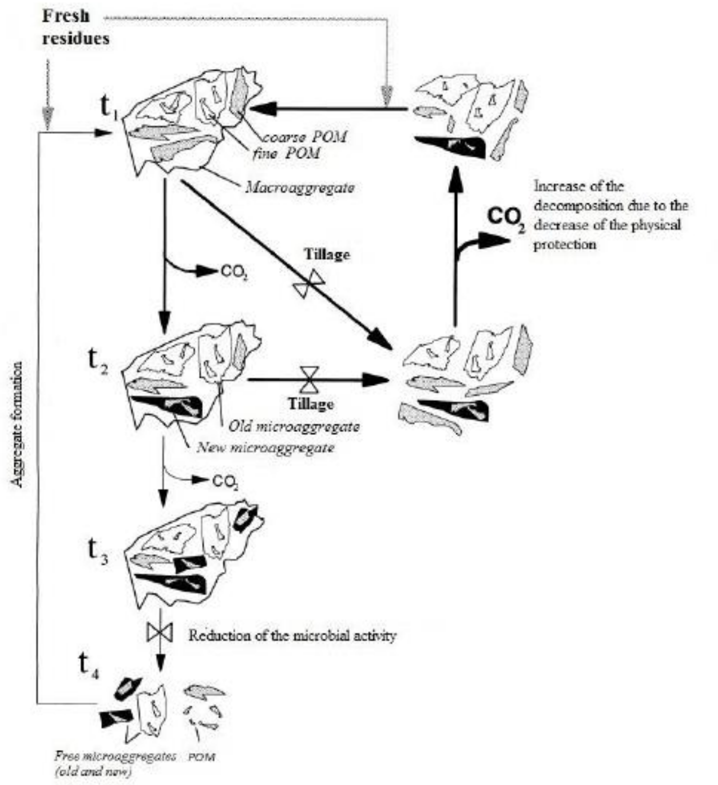


Figura 15. Esquema teórico de la ruptura de agregados por el laboreo. Adaptado de Six *et al*. (2000).

La capacidad de los agregados de proteger y estabilizar SOC está ampliamente documentada (Angers *et al*., 1997; Cambardella and Elliott, 1993; Franzluebbers and Arshad, 1997; Jastrow, 1996; Paustian *et al*., 2000; Six *et al*., 1999, 2000) y se relaciona principalmente con la capacidad, mediante la agregación de partículas, de separar espacialmente el material orgánico y los microorganismos, así como con una reducción de la actividad microbiana debido a una menor difusión del oxígeno dentro de los agregados del suelo (Mikutta *et al*., 2006; Kravchenko *et al*., 2015).

Los agregados del suelo pueden clasificarse según su tamaño y tipo de resistencia a la desestabilización del SOC (Figura 16). De este modo, los macroagregados son las partículas de mayor tamaño, se pueden dividir en macroagregados grandes (> 2000 μm) y macrogaregados pequeños (2000-250 μm), y presentan una alta sensibilidad a factores físicos mostrándose frágiles ante las alteraciones ambientales y de la estructura del suelo (Six, 2004; García-Franco *et al.*, 2020). En esta fracción el SOC se encuentra débilmente protegido y está disponible para la degradación por parte de los microorganismos (Solomon *et al.*, 2000; Six, 2002). Sin embrago, su influencia en la estabilización del SOC es fundamental ya que la formación de los microagregados se realiza dentro de los macroagregados (Pronk *et al*., 2012).

Los microagregados (53-250 μm) juegan un papel importante en la estabilización de SOC a largo plazo (Totsche *et al*., 2018) debido a que muestran resistencia a la degradación física y, por lo tanto, a la pérdida del SOC. La estructura de los microagregados del suelo se define como un sistema bastante estable y complejo, con poros interconectados de diverso tamaño y geometría, que proporcionan una gran interrelación biogeoquímica interna y externa, heterogénea y morfológicamente compleja (Totsche *et al*., 2010). A lo largo del tiempo se desarrollan nuevos microagregados que se establecen dentro de los macroagregados. Estos nuevos microagregados se forman a partir de la materia orgánica fina (fPOM), que se incrusta en las partículas de arcilla y en diferentes productos microbianos, utilizando la materia orgánica gruesa (cPOM) como agente de agregación. Por lo tanto, los residuos de cPOM son esenciales para la formación de nuevos microagregados (Six *et al*., 2000).

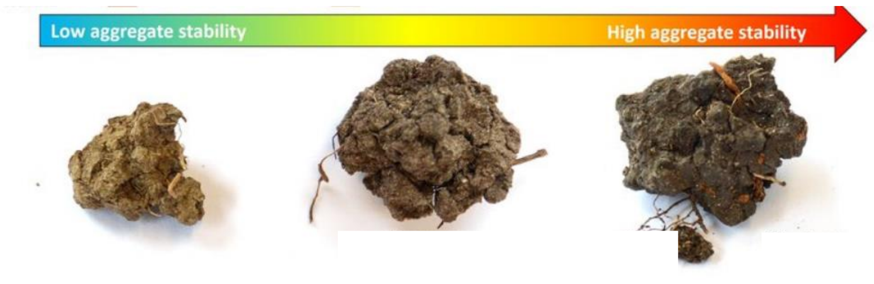


Figura 16. Diferentes grados de estabilidad de los agregados. Adaptado de García-Franco *et al*. (2020).

Las partículas <53 µm están generalmente organizadas en unidades estructurales que implican la presencia de materia orgánica, minerales, así como biomasa microbiana (Tisdall and Oades, 1982; Chenu and Plante, 2006; Asano and Wagai, 2014), es la denominada como fracción de limo y arcilla. Esta fracción junto con los microagregados también ha sido dividida en otras ocasiones como pequeños microagregados (<20 µm) y grandes microagregados (20-250 µm) (Totsche *et al*., 2018). En esta fracción el SOC se encuentra doblemente protegido ante la degradación, mediante la interacción química con las partículas de limo y arcilla, además de incrementar la protección física debido a una mayor estabilidad al absorber SOC (Vicente-Vicente *et al*., 2017). Aunque hay una relación directa entre el porcentaje de limo y arcilla en el suelo y el

SOC ligado a esta fracción, las relaciones entre ambas propiedades son complejas, donde las condiciones ambientales y el tipo de arcillas juegan un papel importante.

Por último, el SOC puede estabilizarse en el suelo bioquímicamente, mediante este proceso, debido a su propia composición química, (compuestos como lignina o polifenoles) el SOC puede ser resintetizado en estructuras complejas de moléculas, a través de procesos de condensación, que pueden impedir la descomposición (Six *et al*., 2002; Lefevre *et al*., 2017).

1.3.5 Principales pérdidas de carbono orgánico en suelos a agrícolas.

En el balance del SOC se producen también salidas de C, de este modo, se genera un flujo donde el C almacenado en el suelo puede volver a la atmósfera. Estas pérdidas se generan principalmente a través de procesos disrupción del suelo como la erosión y el laboreo convencional.

A través de los procesos de erosión se produce el transporte y la deposición de sedimentos que van acompañados de SOC (Wang *et al*., 2014; Martínez-Mena *et al*., 2019) y se fomentan las emisiones a la atmosfera de CO_2 desde los suelos (Lugato *et al*., 2016; Lal, 2019a, 2020b). La erosión se ha demostrado como el principal proceso natural de ruptura y transporte de suelo en los espacios agrícolas (Borrelli *et al*., 2020a), deteriorando altamente a los agregados del suelo (Wei *et al*., 2017). Este proceso tiene importantes efectos en la acumulación y estabilización de la MOS (Berhe *et al*., 2012; López-Vicente *et al*., 2020), pudiendo movilizar gran cantidad de SOC en las áreas de cultivo (Martínez-Mena *et al*., 2008) con lo que se producen pérdidas por escorrentía (Shi y Schulin, 2018) y mineralización (Xiao *et al*., 2018) (Figura 17) y se determina la distribución del SOC en la parcela, generando espacios descarbonizados y áreas con un importante almacenamiento de C (Müller-Nedebock y Chaplot, 2015) .

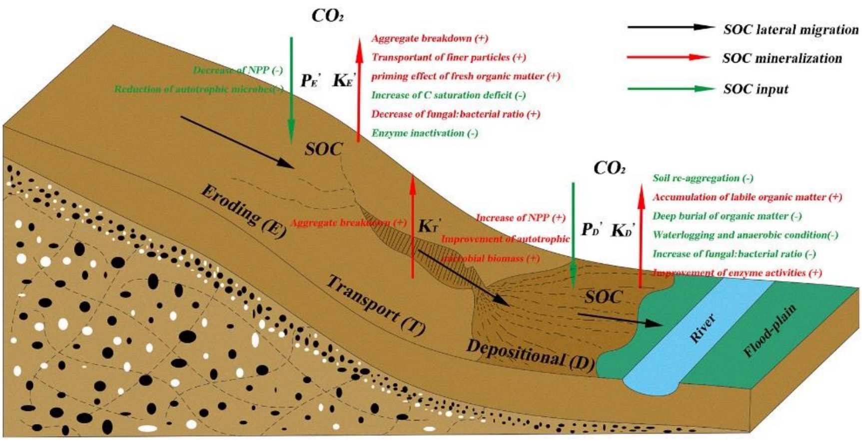


Figura 17. Procesos de erosión y dinámica del SOC en una ladera erosionada. Adaptado de Xiao *et al*. (2018).

Por otro lado, es necesario resaltar que la labranza convencional del suelo fomenta los procesos erosivos y ha sido ampliamente expuesta como una técnica de manejo que provoca una reducción en el contenido de SOM (Balesdent *et al*., 2000, Six *et al*., 2000), especialmente cuando no va acompañada de restos de vegetación (Raiesi y Kabiri, 2017). Además, con un laboreo continuo se reduce la estabilidad estructural del suelo (Plaza-Bonilla *et al*., 2010; Kan *et al*., 2020), provocando la rotura de agregados con lo que se produce un aumento de la mineralización del

SOC y, por lo tanto, se reduce su contenido en el suelo, a la vez que se estimulan las emisiones de CO_2 (Zhang *et al*., 2018).

1.3.6 Los límites de la capacidad de secuestro de carbono orgánico, saturación y potencial de almacenamiento.

La capacidad de los suelos de almacenamiento de C no es finita. Numerosos estudios han demostrado que el suelo tiene un nivel de saturación de C (Six *et al*., 2002; Beare *et al*., 2014). Por lo tanto, la saturación se define como el umbral máximo que tienen los suelos para almacenar C (Dignac *et al*., 2017). Esta inquietud por establecer los límites al almacenamiento de C en el suelo ha llevado a la comunidad científica a desarrollar investigaciones en torno al potencial y la saturación de C en los suelos. De acuerdo con Chenu *et al*. (2019) el potencial de almacenamiento de carbono de una determinada área de suelo puede definirse como "la máxima ganancia en la reserva de SOC alcanzable bajo un clima determinado y una línea de tiempo determinada".

Debido a que la fracción fina mineral (limo fino y arcilla) contiene una gran proporción del C almacenado en los suelos, especialmente en suelos agrícolas (Figura 18), se ha utilizado esta fracción para determinar la capacidad de saturación y el potencial de almacenamiento de C (Six *et al*., 2002, Wiesmeier *et al*., 2014; Chen *et al*., 2019).

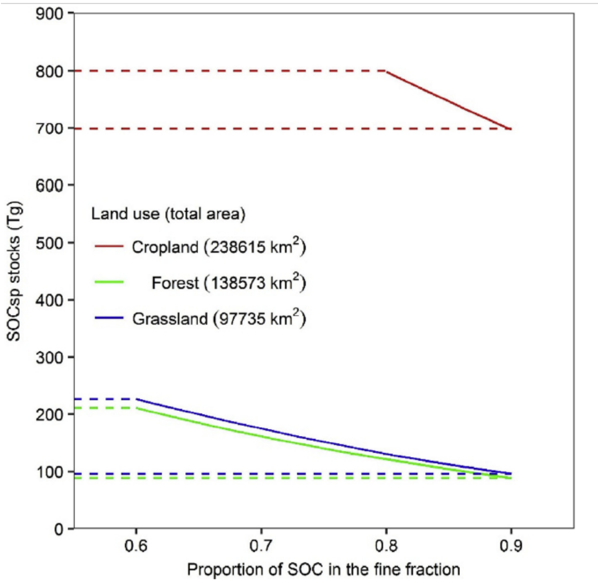


Figura 18. Influencia de la proporción de SOC en la fracción fina dentro de stock de SOC (30 cm) en suelos de Francia. Adaptado de Chen *et al*. (2019).

Por lo tanto, el déficit de C para alcanzar la saturación es obtenido a partir del valor actual de C en la fracción de limo y arcilla. En el estudio realizado por Hassink (1997) se demostró una importante correlación entre el contenido de la fracción fina (<20 µm) y el contenido de SOC de la misma fracción en diferentes regiones templadas y tropicales. A partir de este primer estudio y la ecuación planteada, se han llevado a cabo otros muchos donde partiendo de la capacidad de la fracción de limo y arcilla (<20/<53 µm) de estabilizar C se han desarrollado modelos de regresión para estimar el potencial de almacenamiento de SOC de los suelos agrícolas a diferentes escalas de estudio (Carter *et al*., 2003; Sparrow *et al*., 2006; Zhao *et al*., 2006; Angers, *et al*., 2011; Chen *et al*., 2019).

En los suelos agrícolas el déficit de saturación de C es superior debido a que el contenido en SOC suele ser menor que en espacios forestales o de pastizal. Además, la capacidad de alcanzar la saturación se ve influenciada por el manejo de los suelos agrícolas. A partir de estas evidencias, ampliamente constatadas, Stewart *et al*. (2007) desarrollan el concepto de capacidad de estabilización efectiva donde en un suelo de características idénticas, las prácticas de manejo marcan la capacidad de estabilizar C, aunque el nivel de saturación del suelo sea el mismo (Figura 19).

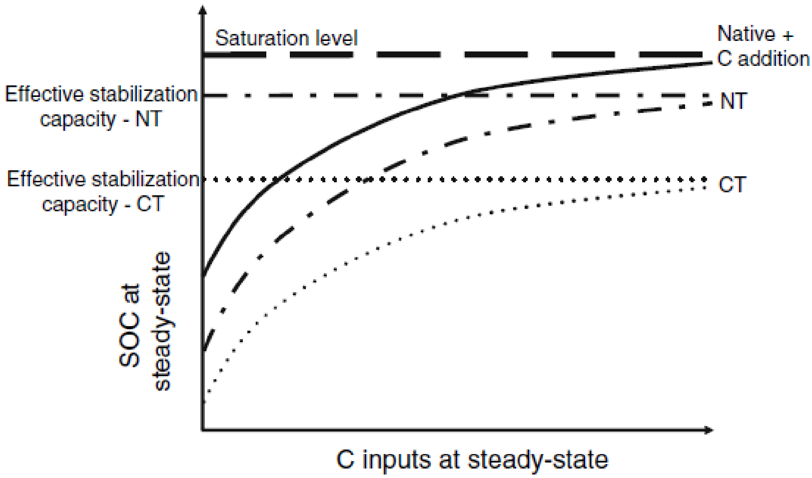


Figura 19. Acumulación y capacidad de estabilización de SOC bajo diferentes manejos (NT: no laboreo; CT: laboreo convencional). Adaptado de Stewart *et al*. (2007).

1.4 Tipologías y manejos del olivar: el estado del arte.

1.4.1 El olivar, un cultivo mediterráneo de escala global.

El olivo (*Olea europaea L.*) fue domesticado, para el aprovechamiento agrícola, hace más de 3.000 años en el área mediterránea (Montararo *et al.*, 2018). En la actualidad, el cultivo de olivar es una de las actividades agrícolas principales en la cuenca mediterránea, donde se encuentran el 95% de las 10,8 Mha que existen de este cultivo a nivel mundial (FAOSTAT, 2017). La importancia de este cultivo no radica exclusivamente en su extensión, sino que además se trata de un cultivo ancestral con gran influencia en aspectos económicos, sociales y culturales (Ojeda-Rivera *et al.*, 2018).

El olivar se extiende por toda la cuenca mediterránea, situándose a lo largo de unos 3.800 kilómetros de este a oeste, entre 30 y 47º de latitud norte. Se trata de un cultivo con una alta adaptación al clima Mediterráneo debido a su capacidad para soportar sequías y su resistencia a las heladas (Arenas-Castro *et al.*, 2020). El cultivo de olivar, tradicionalmente se ha asentado en terrenos de baja capacidad agronómica, donde los suelos no tenían la mejor aptitud, aunque puede adaptarse a suelos con propiedades muy diversas. Esta tendencia a situarse en terrenos marginales ha ido cambiando con la aparición de nuevas variedades, formas de producción y manejo que han convertido el manejo del olivar en un proceso más productivo e intensivo (Infante-Amate *et al.*, 2016).

En España, el cultivo del olivar cubre una superficie de 2.697.445 ha (MAPA, 2018) lo que supone que es el cultivo leñoso con mayor extensión, muy por delante de los frutales o el viñedo, ocupando un 15,8% del total de tierras de cultivo del país. La comunidad andaluza es la región que abarca una mayor área de este cultivo con el 60,4% de las tierras de cultivo de olivar a nivel estatal, que suponen el 9,5% del total de tierras de cultivo del país (MAPA, 2018).

El cultivo de olivar en Andalucía se encuentra bajo un importante dinamismo como se demuestra con el continuo incremento en el número de hectáreas dedicadas a este cultivo, que han pasado de suponer 1.554.771 en 2012 a 1.630.473 en 2018 lo que implica un incremento anual del 4,6%. Este cultivo es un elemento fundamental dentro del agroecosistema regional debido a que representa el 45,9 % de las tierras de cultivo regionales y el 81,5 % de los cultivos leñosos (MAPA, 2018). Su influencia en la comunidad va más allá de lo propiamente agrícola, puesto que existe en torno al cultivo una importante actividad industrial, de transformación, logística y tratamiento de subproductos, con lo que es un subsector estratégico para la región (Egea y Pérez, 2016). La dimensión de este cultivo a nivel regional hace que su importancia sea vital para la generación de empleos y renta, especialmente en las zonas rurales. Por este motivo, la Comunidad ha desarrollado su propia Ley del Olivar de Andalucía (Ley 5/2011 de 6 de octubre) que tienen como objeto “establecer el marco normativo para el mantenimiento y la mejora del cultivo del olivar, el desarrollo sostenible de sus territorios y el fomento de la calidad y la promoción de sus productos” (Art. 1 Ley del Olivar de Andalucía).

En cuanto a la distribución provincial del cultivo dentro de la comunidad andaluza destacan Jaén con un 36% del total la superficie de olivar andaluz (592.867 ha) y Córdoba con un 22% (369.446 ha) muy por delante de Sevilla (13,8%), Granada (12,6%) o Málaga (8,8%). Especialmente importante es la implantación del cultivo en la provincia de Jaén donde ocupa el 90% de las tierras de cultivo con lo que se podría hablar de un monocultivo provincial con una alta especialización, pero también con gran dependencia. En otras provincias como Córdoba o Málaga el olivar ocupa alrededor del 50% de las tierras de cultivo.

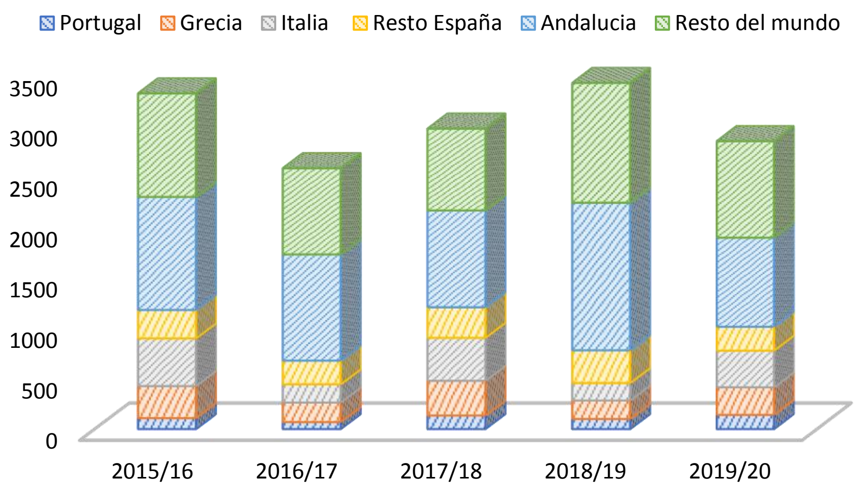


Gráfico 1. Evolución de la producción mundial de aceite de oliva (2015/16 – 2019/20). Elaboración propia a partir de diversas fuentes.

En cuanto a la producción de aceite de oliva, en la Unión Europea se produce aproximadamente el 61% (1.920 Mt) del aceite de oliva mundial (3.103 Mt) (EC, 2020). Por países, España es el líder mundial en producción de aceite de oliva, alcanzando en la campaña 2019/2020 la cifra de 1.121 Mt de aceite de oliva, muy por encima del resto de países europeos, Italia (366 Mt), Grecia (275 Mt) o Portugal (141 Mt) (EC, 2020). El 80% (883.322 t) de la producción nacional y el 45% de la producción europea de aceite de oliva en la campaña 2019/2020 fue producida en Andalucía (AICA, 2019), estas cifras convierten a Andalucía como el referente en la producción de aceite de oliva a nivel mundial (Gráfico 1). Aunque suponen un 32,7% menor que la campaña 2018/2019 donde se alcanzaron 1793 Mt, se encuentran acorde con respecto a la media del último lustro que sitúa la producción en 1,06 Mt de aceite.

1.4.2 Tipología del olivar en Andalucía.

La morfología del olivar andaluz ha ido modificándose a lo largo del tiempo, creando un paisaje característico de la comunidad, con una tipología muy diversa consecuencia de este proceso evolutivo. La influencia antrópica a través de la agricultura ha ido alterando el paisaje del olivar andaluz desde un cultivo multifuncional con bajos rendimientos, amplios marcos de plantación, aprovechamiento silvopastoril y cubiertas vegetales hasta un cultivo intensivo, con altas densidades de árboles, sin asociación con otros cultivos y con altos rendimientos (Andreu-Lara, 2013).

En la actualidad, de acuerdo con el Plan Director del olivar de Andalucía (Junta de Andalucía, 2015), puede establecerse una clasificación de los olivares según su tipología donde se pueden distinguir:

a) Tipo 1: Olivar de bajos rendimientos, olivar con rendimientos iguales o inferiores a 775 kg de aceituna/ha, cultivado en zonas con malas condiciones edafoclimáticas o altas pendientes.

b) Tipo 2: Olivar de alta pendiente, olivar cultivado en suelos con mejores condiciones agronómicas, con pendiente igual o superior al 20%. Debido a la elevada pendiente, no es posible realizar la recolección de la aceituna con medios mecánicos.

c) Tipo 3: Olivar extensivo con densidad igual o inferior a 150 árboles/ha, olivar cultivado con pendiente inferior al 20% y densidad de plantación igual o inferior a 150 árboles/ha, siendo posible la recolección mecanizada de la aceituna.

d) Tipo 4: Olivar extensivo de densidad media, olivar cultivado con pendiente inferior al 20% y densidad de plantación comprendida entre 150 y 180 árboles/ha, siendo posible la recolección mecanizada de la aceituna.

e) Tipo 5: Olivar intensivo, olivar con densidad de plantación comprendida entre 180 y 325 árboles/ha, situado en zonas llanas.

f) Tipo 6: Olivar superintensivo, olivar con una densidad de plantación superior a 325 árboles/ha situado en zonas llanas.

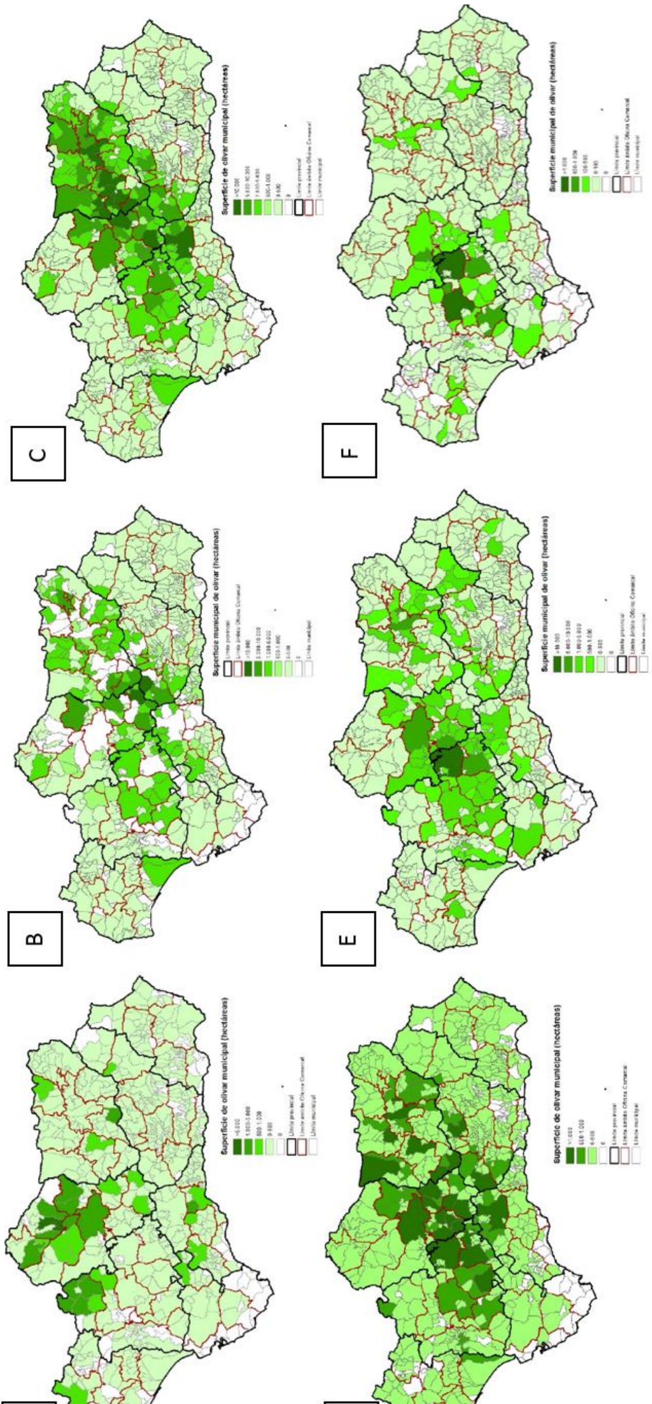


Figura 20. Distribución municipal de la superficie de olivar según tipología. A. Tipo 1, B. Tipo 2, C. Tipo 3, D. Tipo 4, E. Tipo 5 y F. Tipo 6. (Junta de Andalucía, 2015).

Esta amplia tipología del olivar andaluz se distribuye de forma desigual por el territorio de la región (Figura 20), siendo la tipología con mayor extensión la de olivar extensivo con densidad igual o superior a 150 árboles/ha con un 47,5 % de las hectáreas de olivar de la comunidad (Junta de Andalucía, 2017).

Uno de los aspectos más destacables en el olivar andaluz, por su influencia en los manejos agronómicos y la evolución de las propiedades de los suelos, es el alto porcentaje de explotaciones que se sitúan en zonas de pendiente pronunciada. De este modo, un 32,7% de las explotaciones, lo que implica un 26,8% de la superficie total del olivar andaluz, se encuentran en pendientes que superan el 20% (Junta de Andalucía, 2017). Esta distribución del olivar tiene gran influencia en uno de los mayores problemas agroambientales que sufre este cultivo y que pone en cuestionamiento su sostenibilidad a largo plazo, como son los altas tasa de pérdida de suelo debida a la erosión hídrica (Durán-Zuazo *et al*., 2020).

En los últimos años la siembra y el manejo del cultivo de olivar ha sufrido una importante transformación con la aparición del olivar intensivo y superintensivo. Aunque su peso en el total del número de hectáreas es todavía bajo, 14% de olivar intensivo y 1,4% de olivar superintensivo (Junta de Andalucía, 2017), la mayoría de las nuevas plantaciones de olivar en Andalucía se ajustan a estas tipologías. Esta nueva tendencia hacia una mayor densidad de árboles implica importantes cambios en los manejos, un aumento de la cobertura del suelo por el arbolado y de la biomasa generada, lo cual puede tener influencia en las propiedades de los suelos bajo este tipo de plantaciones. Sin embargo, debido a que se trata de plantaciones recientes, los efectos que provocan en las propiedades de los suelos a largo plazo no están demostrados.

1.4.3. Principales prácticas de manejo de los suelos de olivar.

El cultivo del olivar ha experimentado en las últimas décadas una importante transformación que ha afectado de manera significativa a las labores que implican su manejo, pasando de un cultivo donde la mayoría de las labores se realizaban mediante tracción animal y manualmente a un cultivo altamente mecanizado (Infante-Amate, 2014). Está ampliamente reconocido que las prácticas de manejo que se aplican en los cultivos tienen una importante influencia en las propiedades del suelo (Proietti *et al.*, 2014; Amelung *et al*., 2020). Actualmente las principales prácticas de manejo del olivar según mantengan el suelo desnudo o no pueden clasificarse en tres grupos, laboreo, no laboreo y mantenimiento de cubiertas.

1.4.3.1 Laboreo.

El laboreo consiste en alterar los primeros 20 cm de suelo por medios mecánicos (Figura 21). En olivar suelen utilizarse aperos como gradas de discos, vertederas o cultivadores. Dependiendo de la zona y el agricultor, el número de pases anuales suele oscilar entre 2 y 4. Con la práctica del laboreo se pretende mantener las calles libres de vegetación, evitar el encostramiento, favorecer la infiltración de agua en el suelo e incorporar al suelo los residuos superficiales.

Figura 21. Olivar con laboreo. Imagen propia.

Sin embargo, esta práctica ha sido catalogada en multitud de ocasiones como insostenible medioambientalmente (Kairis *et al*., 2013; Telak *et al*., 2020). Entre las consecuencias negativas que el laboreo implica para los suelos de olivar se pueden destacar, el fomento de los procesos erosivos (Sastre *et al*., 2017), el aumento de la aireación del suelo que incrementa la mineralización de la materia orgánica y el descenso en los SOC-S (Parras-Alcántara *et al*., 2013; Bateni *et al*., 2019), además de la pérdida de estabilidad estructural por la degradación de los agregados del suelo (González-Rosado *et al*., 2020a).

Las repercusiones negativas que el continuo laboreo ejerce sobre el suelo, especialmente en zonas de pendiente, ha llevado a buscar alternativas como el laboreo de conservación. Este tipo de laboreo, también conocido como laboreo mínimo o reducido, minimiza tanto la profundidad de la labor (10 cm aproximadamente) como el número de pasadas en la finca, con el objetivo de alterar lo menos posible la capa superficial del suelo. La implementación de esta práctica en el olivar ha sido aceptada como sostenible (Kavvadias y Koubouris, 2019) debido a que reducen la alteración del suelo y favorecen la estabilización de SOC (Kabiri *et al*., 2015).

1.4.3.2 No laboreo.

Está practica de manejo es la alternativa más extendida, en el cultivo de olivar, al laboreo convencional, con el establecimiento del no laboreo (Figura 22) se pretende reducir el número de labores mecánicas, dejando inalterada la capa superficial del suelo. El manejo de olivar bajo no laboreo con suelo desnudo, lleva asociado la aplicación de herbicidas de preemergencia y postemergencia para evitar la proliferación de vegetación en la explotación, con el objetivo de evitar posibles competencias por agua y nutrientes con el olivo.

Figura 22. Olivar bajo no laboreo con suelo desnudo y aplicación de herbicidas. Imagen propia.

La aplicación de no laboreo con herbicidas, ha sido entendida por muchos agricultores como una práctica sostenible debido al menor número de labores realizadas al cultivo. Sin embargo, la utilización de esta práctica está muy cuestionada debido a que reduce las entradas de SOC en el suelo debido a la falta de desarrollo de vegetación espontánea y al mantenimiento de los restos de poda en superficie (González-Rosado *et al*., 2021), con lo que son fácilmente arrastrables por la escorrentía en explotaciones con cierta pendiente (Hernández *et al*., 2005). Por otro lado, el uso continuado de herbicidas sobre la capa superficial del suelo provoca problemas de encostramiento, aumentando la compactación de suelo y favoreciendo los procesos de escorrentía y, por lo tanto, de erosión y pérdida de SOC (Castro *et al*., 2008).

1.4.3.3 Cubiertas vegetales en olivar.

El desarrollo de cubiertas vegetales en los olivares andaluces ha experimentado un considerable incremento en los últimos años, en la actualidad el 37% de la superficie de olivar se encuentra bajo este manejo (MAPA, 2018). Esto se debe principalmente a su obligación como requisito para cumplir con la gestión y las buenas condiciones agrarias y medioambientales, establecidas por la condicionalidad en la PAC, para parcelas con una pendiente superior al 10 %, las cuales deben mantener una cubierta de anchura mínima de 1m. En este sistema de manejo el suelo se mantiene cubierto bien mediante una cubierta vegetal viva (espontánea o sembrada) o con una cubierta inerte.

a. Cubiertas vivas.

En este tipo de manejo se permite el desarrollo de vegetación bien por siembra o de forma espontánea para después, generalmente previo a los meses de verano, pasar a su siega, bien mecánicamente (con segadoras o desbrozadoras), de forma química (herbicidas) o con la introducción de ganado. Las cubiertas vivas pueden ser de dos tipos:

1. Cubiertas espontáneas: son las más generalizadas en los olivares con cubierta, se trata de dejar crecer la flora arvense ("malas hierbas"). En suelos de olivar degradados estas cubiertas no siempre se desarrollan de la forma adecuada, generando poca biomasa y no cubriendo un porcentaje alto del suelo desnudo, con lo que los problemas relacionados con procesos erosión no son resueltos.

2. Cubiertas sembradas: consiste en la siembra en las calles del olivar de una o varias especies vegetales generalmente gramíneas como avena (*Avena sativa*), cebada (*Hordeum vulgare*), centeno (*Secale cereale*) o leguminosas como haba (*Vicia faba*) (Figura 23), trébol (*Trifolium sp*.) o veza (*Vicia sativa*) que generan una alta cobertura del suelo y un amplio sistema radicular.

Figura 23. Cubierta sembrada de haba en olivar joven. Imagen propia.

La implantación de una cubierta vegetal viva en las calles de olivar debe evitar las competencias tanto en agua como en nutrientes con el cultivo del olivo y no impedir las labores propias de un olivar productivo. Numerosos estudios han demostrado que la instalación de cubiertas vegetales en las explotaciones de olivar es una estrategia positiva para enfrentar los problemas de sostenibilidad de los suelos de olivar, de este modo, las cubiertas influyen en:

- Reducir las pérdidas de suelo y SOC por escorrentía, cubriendo un alto porcentaje del suelo entre las calles del olivar (Hernández *et al*., 2005; Durán-Zuazo *et al*., 2020).
- Aumentar la infiltración con respecto a suelos desnudos debido al aumento de la porosidad (Palese *et al*., 2014; Sastre *et al*., 2018a).
- Mejorar la estabilidad estructural del suelo a través de una mayor agregación de las partículas, con el desarrollo de macroagregados, donde las raíces se han constatado como elementos de gran importancia en su constitución (López-Bellido *et al*., 2017).
- Incrementar los niveles de entrada de SOC en el suelo a través de la generación de biomasa en el desarrollo de la cubierta (Vicente-Vicente *et al*., 2017; Sastre *et al*., 2018b).
- Ampliar la riqueza de especies, puesto que el incremento de la biodiversidad repercute en diversas funciones dentro del agroecosistema (Sánchez *et al.,* 2015; Gómez *et al.,* 2018).

b. Cubiertas inertes.

Las cubiertas inertes en olivar suelen derivar del picado de restos de la poda de los árboles (ramas y hojas) que habitualmente tiene una periodicidad bianual. Los restos de poda aplicados como cubierta generan una importante biomasa (entre 1,3 - 3 t ha^{-1}) (Ordoñez *et al*., 2007a) que queda sobre la superficie logrando un efecto de acolchado (Repullo *et al*., 2012). Este tipo de cubierta se puede combinar con otros tipos de cubiertas vivas siendo complementarias, ya que no suele ocupar el total de la calle en las tipologías de olivar de marco amplio, quedando reducida a un cordón de material vegetal en el centro de la calle.

Figura 24. Olivar con cubierta de restos de poda olivar.

Tradicionalmente los restos de poda del olivar eran eliminados mediante quemas controladas, sin embargo, el triturado de los restos de poda y su posterior aplicación al suelo del olivar se ha extendido entre los manejos habituales de los agricultores (Calatrava y Franco, 2011). Numerosos estudios han avalado su influencia en la calidad del suelo (Moreno-García *et al*., 2018), en el incremento de humedad y SOC (Lozano-

García *et al*., 2011) y en la reducción de pérdidas de suelo y nutrientes (Rodríguez-Linaza *et al*., 2008).

1.4.4. La pérdida de suelo en los olivares de Andalucía.

La erosión hídrica en el olivar se ha determinado como uno de los principales procesos en la degradación de los suelos, debido principalmente a las pérdidas de suelo y con ello SOC y nutrientes (Rodríguez-Sousa *et al*., 2019). El régimen pluviométrico en el clima mediterráneo, que suele concentrar las precipitaciones en eventos cortos e intensos, unido al gran porcentaje de olivar que en Andalucía se instala en terrenos con pendiente, provoca que este cultivo tenga una importante vulnerabilidad natural ante procesos erosivos (Taguas y Gómez, 2015; Rodrigo-Comino *et al*., 2018). A estas características climáticas y morfológicas de los olivares andaluces se le añade que los suelos, por lo general, se mantienen desprovistos de cobertura vegetal a lo largo del año, mediante laboreo o con el uso de herbicidas. Además, los suelos de olivar se caracterizan en su mayoría por ser suelos con bajos niveles de OM lo que incrementa su susceptibilidad ante la erosión (Panagos *et al*., 2014; Borrelli *et al*., 2020b).

La importancia del fenómeno de la erosión en los olivares andaluces (Figura 25) ha llevado a que en las últimas décadas se haya generado una cuantiosa bibliografía relacionada con las pérdidas de suelo en este cultivo. Aunque las tasas de erosión pueden ser muy dispares, numerosos estudios han demostrado los altos niveles (por encima de 10 t ha^{-1} $año^{-1}$) que tienen lugar en los olivares andaluces bajo manejos con suelos desnudos (Pastor *et al*., 2001; Gómez *et al*., 2004, 2009a; Francia *et al*., 2006; Mabit *et al*., 2012) con un ritmo insostenible de erosión anual desde hace décadas, que incluso se han ido agravando con el paso del tiempo (Vanwalleghem *et al*., 2011).

Figura 25. Olivar afectado por erosión en cárcavas (imagen propia).

Ante la degradación de los suelos, la mayoría de los estudios que afrontan esta problemática han concluido que la mejor alterativa a los manejos convencionales para reducir las tasas de erosión es la cobertura del suelo. Para ello, las estrategias más recomendadas son la inclusión de cubiertas vegetales en las calles del olivar tanto con cubiertas espontáneas (Taguas *et al*., 2010, 2017; Durán-Zuazo *et al*., 2020; Carbonell-Bojollo *et al*., 2020) como con cubiertas sembradas (Pastor, 2008; Duran-Zuazo y Rodríguez-Pleguezuelo, 2008; Gómez *et al*., 2009b; Repullo-Ruibérriz de Torres *et al*., 2014; 2018) o la aplicación de restos de poda y cosecha (Rodríguez-Lizana *et al*., 2008; Parras-Alcántara *et al*., 2016; Rodrigo-Comino *et al*., 2020). En el control de los altos ratios de erosión por parte de la cobertura, el porcentaje de suelo cubierto es fundamental, para ello se estima que por encima del 20 % del suelo debe estar cubierto (Espejo-Pérez *et al*., 2013) aunque otros autores sugieren porcentajes superiores al 40 % (Sastre *et al*., 2017).

1.4.5. El olivar ecológico.

El olivar ecológico ha sufrido un importante incremento en el número de hectáreas en los últimos años en Andalucía, pasando en la última década de alrededor de 40.000 ha (2008) a 77.000 ha (2018), con lo que representa el 5% del olivar de Andalucía (Aforo de olivar, 2018). Este tipo de manejo tiene una normativa específica (Reglamento (CE) nº 889/2008) bajo la cual se regulan las prácticas aplicables para obtener la catalogación de olivar ecológico.

El manejo del olivar ecológico suele ir acompañado del mantenimiento de una cubierta permanente que se controla a través de un mínimo laboreo, corte mecánico o la introducción de ganado en el olivar (Figura 26). Además, la reposición de nutrientes extraídos en las cosechas se realiza habitualmente mediante el uso de enmiendas orgánicas como compost o estiércol, que se han demostrado como positivas en el incremento de la fertilidad de los suelos de olivar (Fernández-Hernández *et al*., 2014; Madejón *et al*., 2016).

Figura 26. Olivar ecológico con manejo de la cubierta mediante caballos. Imagen propia.

Los efectos positivos de este sistema de manejo sobre los suelos han sido demostrados en diferentes investigaciones tanto para la restauración de suelos degradados (Pleguezuelo *et al*., 2018) como la reducción de tasas de erosión (Ordoñez *et al*., 2007b; Durán-Zuazo *et al*., 2020), el aumento de la diversidad biológica (García *et al*., 2009) o los incrementos de secuestro de C (Parras-Alcántara y Lozano-García, 2014).

La orientación de la nueva PAC (2021-2027) hacia una influencia mayor de cuestiones ambientales en los pagos, a la vez que se desarrollan estrategias europeas (European Green Deal) encaminadas a una mayor sostenibilidad de los recursos naturales, hace que el interés hacia sistemas de manejo sostenibles en el largo plazo se haya incrementado. Para la transformación y extensión del manejo del olivar hacia agroecosistemas que aporten mayores beneficios ambientales, la valorización de los servicios ecosistémicos a partir de su inclusión en las políticas agrarias y ambientales puede ser un aspecto fundamental en los próximos años.

1.5 Referencias.

Abbas, F., Hammad, H., Ishaque, W., Farooque, A., Bakhat, H., Zia, Z., Fahad, S., Farhad, W., Cerdá, A., 2020. A review of soil carbon dynamics resulting from agricultural practices. *Journal of Environmental Management*. 268. 110319. https://doi.org/10.1016/j.jenvman.2020.110319

Abbas, F., Mohkum Hammad, H., Fahad, S., Cerda, A., Rizwan, M., Farhad, W., Ehsan, S., Faiq Bakhat, H., 2017. Agroforestry: a sustainable environmental practice for carbon sequestration under the climate change scenarios—a review. *Environmental Science & Policy*. 24, 11177–11191. https://doi.org/10.1007/s11356-017-8687-0.

Abd-Elmabod, S.K., Muñoz-Rojas, M., Jordán, A., Anaya-Romero, M., Phillips, J.D., Jones, L., Zhang, Z., Pereira, P., Fleskens, L., der Ploeg, M., 2020. Climate change impacts on agricultural suitability and yield reduction in a Mediterranean region. *Geoderma*, 374, 114453. https://doi.org/10.1016/j.geoderma.2020.114453

Abdelrahman, H., Cocozza, C., Olk, D. C., Ventrella, D., Montemurro, F., Miano, T., 2020. Changes in labile fractions of soil organic matter during the conversion to organic farming. *Journal of Soil Science and Plant Nutrition*, 1-10. https://doi.org/10.1007/s42729-020-00189-y

Aforo de Olivar, 2019. Consejería de Agricultura, Pesca y Medio Ambiente, Junta de Andalucía.https://juntadeandalucia.es/export/drupaljda/Presentaci%C3%B3n_ACEITUNA%20ACEITE_2019-2020_comentarios_%20v4.pdf

AICA, 2020. Agencia de Información y Control de Alimentos. Ministerio de Agricultura, Pesca y Alimentación. https://www.aica.gob.es/

Alons, G., 2017. Environmental policy integration in the EU's common agricultural policy: greening or greenwashing? *Journal of European Public Policy*, *24*(11), 1604-1622. https://doi.org/10.1080/13501763.2017.1334085

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., ... & Chabbi, A. (2020). Towards a global-scale soil climate mitigation strategy. *Nature communications*, *11*(1), 1-10. https://doi.org/10.1038/s41467-020-18887-7

Andersson, S., Nilsson, S. I., 2001. Influence of pH and temperature on microbial activity, substrate availability of soil-solution bacteria and leaching of dissolved organic carbon in a mor humus. *Soil Biology and Biochemistry*, *33*(9), 1181-1191. https://doi.org/10.1016/S0038-0717(01)00022-0

Andreu Lara, C., Delgado, B., Ojeda Rivera, J.F. y Infante Amate, J., 2013. Los olivares andaluces y sus paisajes distintivos del mundo mediterráneo. *Revista de estudios regionales*, *96*, 267-291.

Angileri, V., Fasbender, D., Van Eupen, C., Tzilivakis, J., Warner, D., Devos, W., Terres, J. M., 2017. Using the Ecological Focus Area (EFA) calculator to assess the potential impact of EFA implementation on biodiversity and ecosystem services. Luxembourg: Joint Research Centre (JRC), European Commission. http://publications.jrc.ec.europa.eu/repository

Angers, D, A., Arrouays, D., Saby, N, P, A., Walter, C., 2011. Estimating and mapping the carbon saturation deficit of French agricultural topsoils. *Soil Use and Management*, 27, 448–552.

Angers, D.A., Recous, S., Aita, C., 1997. Fate of carbon and nitrogen in water-stable aggregates during decomposition of (CN)-C-13-N-15-labelled wheat straw in situ. *European Journal of Soil Science*, 48 (2), 295–300. https://doi.org/10.1111/j.1475-2743.2011.00366.x

Angst, G., Messinger, J., Greiner, M., Häusler, W., Hertel, D., Kirfel, K., Mueller, C. W., 2018. Soil organic carbon stocks in topsoil and subsoil controlled by parent material, carbon input in the rhizosphere, and microbial-derived compounds. *Soil Biology and Biochemistry*, *122*, 19-30. https://doi.org/10.1016/j.soilbio.2018.03.026

Arenas-Castro, S., Gonçalves, J. F., Moreno, M., Villar, R., 2020. Projected climate changes are expected to decrease the suitability and production of olive varieties in southern Spain. *Science of The Total Environment*, *709*, 136161. https://doi.org/10.1016/j.scitotenv.2019.136161

Armas-Herrera, C.M., Dignac, M.F., Rumpel, C., Arbelo, C.D., Chabbi, A., 2016. Management effects on composition and dynamics of cutin and suberin in topsoil under agricultural use. *European Journal of Soil Science*, 67:360–373. https://doi.org/10.1111/ejss.12328

Asano, M., Wagai, R., 2014. Evidence of aggregate hierarchy at micro-to submicron scales in an allophanic Andisol. *Geoderma*, 216, 62–74. https://doi.org/10.1016/j.geoderma.2013.10.005

Bagyaraj, D.J., Nethravathi, C.J., Nitin, K.S., 2016. Soil biodiversity and arthropods: Role in soil fertility. In *Economic and ecological significance of arthropods in diversified ecosystems* (pp. 17-51). Springer, Singapore. https://doi.org/10.3390/agriculture3040629

Baiano, S., Morra, L., 2017. Particulate and Mineral-Associated Organic Carbon in Aggregates as Affected by Biowaste Compost Applications in a Mediterranean Vegetables Cropping System. *Communications in Soil Science and Plant Analysis*, *48*(4), 383-394. https://doi.org/10.1080/00103624.2016.1269798

Balesdent, J., Chenu, C., Balabane, M., 2000. Relationship of soil organic matter dynamics to physical protection and tillage. *Soil and tillage research*, *53*(3-4), 215-230. https://doi.org/10.1016/S0167-1987(99)00107-5

Barrios, E., 2007. Soil biota, ecosystem services and land productivity. *Ecological economics*, *64*(2), 269-285. https://doi.org/10.1016/j.ecolecon.2007.03.004

Bateni, C., Ventura, M., Tonon, G., Pisanelli, A., 2019. Soil carbon stock in olive groves agroforestry systems under different management and soil characteristics. *Agroforestry System*, 1-11. https://doi.org/10.1007/s10457-019-00367-7.

Batjes, N., 2014. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science*, 65,10–21. https://doi.org/10.1111/ejss.12114_2

Batjes, N., 2016. Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global soil carbon stocks. *Geoderma*, *269*, 61–68. https://doi.org/10.1016/j.geoderma.2016.01.034

Bauer, A., Black, A.L., 1992. Organic carbon effects on available water capacity of three soil textural groups. *Soil Science Society of America,Proceedings*, 56, 248–254. https://doi.org/10.2136/sssaj1992.03615995005600010038x

Baveye, P. C., Berthelin, J., Tessier, D., Lemaire, G., 2018. The "4 per 1000" initiative: A credibility issue for the soil science community? *Geoderma*, *309*, 118–123. https://doi.org/10.1016/J.GEODERMA.2017.05.005

Baveye, P. C., Baveye, J., Gowdy, J., 2016. Soil "ecosystem" services and natural capital: Critical appraisal of research on uncertain ground. *Frontiers in Environmental Science*, *4*, 41. https://doi.org/10.3389/fenvs.2016.00041

BDS, 2020. EU Biodiversity Strategy for 2030. Web access: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/actions-being-taken-eu/eu-biodiversity-strategy-2030_en.

Beare, M.H., Mcneill, S.J., Curtin, D., Parfitt, R.L., Jones, H.S., Dodd, M.B., Sharp, J., 2014. Estimating the organic carbon stabilisation capacity and saturation deficit of soils: a New Zealand case study. Biogeochemistry 120, 71–87. https://doi.org/10.1007/s10533-014-9982-1

Berhe, A. A., Harden, J. W., Torn, M. S., Kleber, M., Burton, S. D., Harte, J., 2012. Persistence of soil organic matter in eroding versus depositional landform positions. *Journal of Geophysical Research: Biogeosciences*, *117*(G2). https://doi.org/DOI:%2010.1029/2011JG001790

Bochet, E., 2015. The fate of seeds in the soil: a review of the influence of overland flow on seed removal and its consequences for the vegetation of arid and semiarid patchy ecosystems. *Soil*, 1, 131–146. https://doi.org/10.5194/soil-1-131-2015.

Bogunovic, I., Telak, LJ., Pereira, P., 2020. Agriculture management impacts on soil properties and hydrological response in Istria (Croatia). *Agronomy*, *10*(2), 282. https://doi.org/10.3390/agronomy10020282

Bolan, N.S., Adriano, D.C., de la Luz, M., 2004. Dynamics and Environmental Significance of Dissolved Organic Matter in Soil. Doctoral dissertation. Regional Institute Limited.

Bombino, G., Denisi, P., Gómez, J. A., Zema, D. A., 2020. Mulching as best management practice to reduce surface runoff and erosion in steep clayey olive groves. *International Soil and Water Conservation Research*. https://doi.org/10.1016/j.iswcr.2020.10.002

Borges, O., Raimundo, F., Coutinho, J., Gonçalves, B., Oliveira, I., Martins, A., Madeira, M., 2018. Carbon fractions as indicators of organic matter dynamics in chestnut orchards under different soil management practices. *Agroforestry systems*, *92*(2), 301-310. https://doi.org/10.1007/s10457-017-0088-3

Borrelli, P., Alewell, C., Alvarez, P., Anache, J., Baartman, J.E.M., Ballabio, C., Bezak, N., Biddoccu, M., Cerdà, A., Chalise, D., Panagos, P., 2020a. Soil erosion modelling: A global review and statistical analysis. Disponible en: https://eartharxiv.org/repository/object/1934/download/4058/

Borrelli, P., Robinson, D. A., Panagos, P., Lugato, E., Yang, J. E., Alewell, C., Ballabio, C., 2020b. Land use and climate change impacts on global soil erosion by water (2015-2070). *Proceedings of the National Academy of Sciences*, *117*(36), 21994-22001. https://doi.org/10.1073/pnas.2001403117

Bouma, J., 2020. Soil security as a roadmap focusing soil contributions on sustainable development agendas. *Soil Security*, *1*, 100001. https://doi.org/10.1016/j.soisec.2020.100001

Bouma, J., Montanarella, L., Evanylo, G., 2019. The challenge for the soil science community to contribute to the implementation of the UN Sustainable Development Goals. *Soil Use and Management*, 1–9. https://doi.org/10.1111/sum.12518.

Calatrava, J., Franco J.A., 2011. Using pruning residues as mulch: analysis of its adoption and process of diffusion in Southern Spain olive orchards. *Journal of Environmental Management*, 92, 620–629. https://doi.org/10.1016/j.jenvman.2010.09.023

Cambardella, C. A., Elliott, E. T., 1994. Carbon and nitrogen dynamics of soil organic matter fractions from cultivated grassland soils. *Soil Science Society of America Journal*, *58*(1), 123-130. https://doi.org/10.2136/sssaj1994.03615995005800010017x

Cambardella, C. A., Elliott. E, T., 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. *Soil Science Society of America Journal* 57, 1071–1076. https://doi.org/10.2136/sssaj1993.03615995005700040032x

Cambardella, C.A., Elliot, E.T., 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. *Soil Science Society of America Journal*, 56, 777–783. https://doi.org/10.2136/sssaj1992.03615995005600030017x

Campbell, E. E., Paustian, K., 2015. Current developments in soil organic matter modeling and the expansion of model applications: a review. *Environmental Research Letters*, *10*(12), 123004. https://doi.org/10.1088/1748-9326/10/12/123004

Carbonell-Bojollo, R., Moreno-García, M., Ordóñez-Fernández, R., García-Tejero, I.F., Cárceles-Rodríguez, B., Durán-Zuazo, V.H., de Torres, M.A.R.R., 2020. Efficient Groundcovers in Mediterranean Olive Groves Under Changing Climate. In *Resources Use Efficiency in Agriculture* (pp. 729-760). Springer, Singapore. https://doi.org/10.1007/978-981-15-6953-1_20

Cardinael, R., Chevallier, T., Cambou, A., Béral, C., Barthès, B.G., Dupraz, C., Chenu, C., 2017. Increased soil organic carbon stocks under agroforestry: a survey of six different sites in France. *Agriculture, Ecosystem and Environment*, 236, 243–255. https://doi.org/10.1016/j.agee.2016.12.011

Carter, M.R., Angers, D.A., Gregorich, E.G., Bolinder M.A., 2003. Characterizing organic matter retention for surface soils in eastern Canada using density and particle size fractions. *Canadian Journal of Soil Science*, 83, 11–23. https://doi.org/10.4141/S01-087

Castro, J., Fernández, O.E., Rodríguez, P.C.R., Lallena, A.M., Sierra, M., Aguilar, J., 2008. Effects of different olive-grove management systems on the organic carbon and nitrogen content of the soil in Jaen (Spain). *Soil Tillage Research*, 98:56–67. https://doi.org/10.1016/j.still.2007.10.002

Chabbi, A., Lehmann, J., Ciais, P., Loescher, H. W., Cotrufo, M. F., Don, A., Rumpel, C., 2017. Aligning agriculture and climate policy. *Nature Climate Change*, *7*(5), 307-309. https://doi.org/10.1038/nclimate3286

Chan, C., Kay, B.D., Gregorich, E.G., 2007. Factors influencing mineralizable carbon in a landscape with variable topography. Canadian Journal of Soil Science., 87, 495–509. https://doi.org/10.4141/CJSS07022

Chambers, A., Lal, R., Paustian, K., 2016. Soil carbon sequestration potential of US croplands and grasslands: Implementing the 4 per Thousand Initiative. Journal of Soil and Water Conservation, 71, 68A–74A. https://doi.org/10.2489/jswc.71.3.68A

Chen, S., Arrouays, D., Angers, D. A., Martin, M. P., Walter, C., 2019. Soil carbon stocks under different land uses and the applicability of the soil carbon saturation concept. *Soil and Tillage Research*, *188*, 53-58. https://doi.org/10.1016/j.still.2018.11.001

Chenu, C., Angers, D. A., Barré, P., Derrien, D., Arrouays, D., Balesdent, J., 2019. Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. *Soil and Tillage Research*, *188*, 41-52. https://doi.org/10.1016/j.still.2018.04.011

Chenu, C., Plante, A. F., 2006. Clay-sized organo-mineral complexes in a cultivation chronosequence: revisiting the concept of the ‘‘primary organo-mineral complex’’. *European Journal of Soil Science*, *57*, 596–607. https://doi.org/10.1111/j.1365-2389.2006.00834.x

Chevallier, T., 2011. Physical Protection of Organic Carbon in Soil Aggregates. In: Gliński J., Horabik J., Lipiec J. (eds) Encyclopedia of Agrophysics. Encyclopedia of Earth Sciences Series. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-3585-1_197

Choudhury, B.U., Das, P.T., Ngachan, S.V., Islam, M., Das, A., 2014. Land Use Land Cover Change Detection, Soil Health Assessment and Socio-Economy in Northeast India: A Remote Sensing and GIS Approach. vol. 7. Research Bulletin, NAIP Publication, pp. 1–53.

CMNUCC, 1992. Convención Marco de las Naciones Unidas sobre el Cambio Climático. Disponible en: https://unfccc.int/resource/docs/convkp/convsp.pdf

De Bernardi, P., Azucar, D., 2020. The Food System Grand Challenge: A Climate Smart and Sustainable Food System for a Healthy Europe. In Innovation in Food Ecosystems (pp. 1-25). Springer, Cham. https://doi.org/10.1007/978-3-030-33502-1_1

De Blécourt, M., Gröngröft, A., Baumann, S., Eschenbach, A., 2019. Losses in soil organic carbon stocks and soil fertility due to deforestation for low-input agriculture in semi-arid southern Africa. *Journal of Arid Environments*, *165*, 88-96. https://doi.org/10.1016/j.jaridenv.2019.02.006

Desa, U. N., 2019. World population prospects 2019: Highlights. New York (US): United Nations Department for Economic and Social Affairs.

Devine, S., Markewitz, D., Hendrix, P., Coleman, D., 2014. Soil Aggregates and Associated Organic Matter under Conventional Tillage, No-Tillage, and Forest Succession after Three Decades. *Plos ONE*, 9. https://doi.org/10.1371/journal.pone.0084988

Diacono, M., Montemurro, F., 2011. Long-term effects of organic amendments on soil fertility. In *Sustainable agriculture volume 2* (pp. 761-786). Springer, Dordrecht. https://doi.org/10.1007/978-94-007-0394-0_34

Dignac, M.F., Derrien, D., Barré, P., Barot, S., Cécillon, L., Chenu, C., Chevallier, T., Freschet, G.T., Garnier, P., Guenet, B., Hedde, M., 2017. Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. *Agronomy for Sustainable Development*, 37, 14. https://doi.org/10.1007/s13593-017-0421-2

Dominati, E., Patterson, M., Mackay, A., 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecological Economics.* 69, 1858–1868. https://doi.org/10.1016/j.ecolecon.2010.05.002

Duran-Zuazo, V.H., Rodriguez Pleguezuelo, C.R., Martin Peinado, F.J., de Graaff, J., Francia Martinez, J.R., Flanagan, D.C., 2011. Environmental impact of introducing plant covers in the taluses of terraces: implications for mitigating agricultural soil erosion and runoff. *Catena* 84, 79–88. https://doi.org/10.1016/j.catena.2010.10.

Durán-Zuazo, V.H., Rodríguez, B.C., García-Tejero, I.F. Gálvez Ruiz, B., Cuadros T.S., 2020. Benefits of organic olive rainfed systems to control soil erosion and runoff and improve soil health restoration. *Agronomy for Sustainable Development*, 40**,** 41. https://doi.org/10.1007/s13593-020-00644-1

Duran-Zuazo, V.H., Rodriguez-Pleguezuelo, C.R., 2008. Soil-erosion and runoff prevention by plant covers. A review. *Agronomy for Sustainable Development,* 28:65–86. https://doi.org/10.1051/agro:2007062

Dwivedi, D., Riley, W.J., Torn, M.S., Spycher, N., Maggi, F., Tang, J.Y., 2017. Mineral properties, microbes, transport, and plant-input profiles control vertical distribution and age of soil carbon stocks. *Soil Biology and Biochemistry*, 107, 244–259. https://doi.org/10.1016/j.soilbio.2016.12.019

Dyson, F. J., 1977. Can we control the carbon dioxide in the atmosphere? *Energy*, *2*(3), 287-291. https://doi.org/10.1016/0360-5442(77)90033-0

Egea, P., Pérez, P.L., 2016. Sustainability and multifunctionality of protected designations of origin of olive oil in Spain. *Land Use Policy*, 58,264–275. https://doi.org/10.1016/j.landusepol.2016.07.017

Elliot, E.T., Cambardella, C.A., 1991. Physical separation of soil organic matter. *Agriculture, Ecosystems and Environment*, 34, 407-419.

Eskelinen, A., Stark, S., Mannisto, M., 2009. Links between plant community composition, soil organic matter quality and microbial communities in contrasting tundra habitats. *Oecologia* 161, 113–123.

EU Climate Law, 2020. Web address: https://ec.europa.eu/clima/policies/eu-climate-action/law_en

EC, 2020. European Commisson. Dashboard: olive oil.https://ec.europa.eu/info/food-farming-fisheries/farming/facts-and-figures/markets/prices/price-monitoring-sector/plant-products/olive-oil_es

EC, 2018. Proposal for a Regulation of the European Parliament and of the Council Establishing Rules on Support for Strategic Plans to be drawn up by Member States under the Common Agricultural Policy (CAP Strategic Plans) and Financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD)"; European Commission: Brussels, Belgium.
Available online: https://eurlex.europa.eu/resource.html?uri=cellar:aa85fa9a-65a0-11e8-ab9c-01aa75ed71a1.0003.02/DOC_1&format=PDF

EC, 2013. Agricultural policy perspectives briefs. Agriculture and Rural Development - N° 5 Dec. 2013 - Overview of CAP Reform 2014–2020.

EC, 2019. The European Green Deal. COM (2019) 640 final.

EEA, 2017, *Climate change, impacts and vulnerability in Europe 2016 — An indicator-based report*, EEA Report No 1/2017, European Environment Agency. https://www.eea.europa.eu/publications/climate-change-impacts-and-vulnerability-2016).

EEA, 2019. Climate change adaptation in the agriculture sector in Europe. (https://www.eea.europa.eu/publications/cc-adaptation-agriculture) accessed 20 September 2020.

Eyhorn, F., Muller, A., Reganold, J. P., Frison, E., Herren, H. R., Luttikholt, L., Smith, P., 2019. Sustainability in global agriculture driven by organic farming. *Nature Sustainability*, *2*(4), 253-255. https://doi.org/10.1038/s41893-019-0266-6

Espejo-Pérez, A. J., Rodríguez-Lizana, A., Ordóñez, R., & Giráldez, J. V. (2013). Soil loss and runoff reduction in olive-tree dry-farming with cover crops. *Soil Science Society of America Journal*, *77*(6), 2140-2148.

F2F, 2020. Farm to Fork Strategy. Disponible en: https://ec.europa.eu/food/farm2fork_en.

Falco, L., Coviella, C., 2016. Contribution of Amynthas gracilis (Megascolecidae) and Octolasion cyaneum (Lumbricidae) to soil physical stability: a mesocosm experiment. *Revista Facultad De Ciencias Agrarias Uncuyo*, 48 (1), 115–127.

FAO, 2015. Food and agriculture organization of the United Nations: FAO statistical pocketbook, 2015. http://www.fao.org/3/a-i4691e.pdf

FAO, 2016, *Climate change and food security: Risks and responses*, FAO No 1/2016, Food and Agriculture Organization of the United Nations, Rome. Disponible en: http://www.fao.org/3/a-i5188e.pdf

FAO, 2017. Soil Organic Carbon: The Hidden Potential. Food and Agriculture Organization of the United Nations, Rome, Italy. Disponible en: http://www.fao.org/3/I6937EN/i6937

FAOSTAT, 2014. Food and Agriculture Organization of the United Nations. Disponible en: http://www.fao.org/3/a-i3671e.pdf

FAOSTAT, 2017. Disponible en: http://faostat.fao.org

Feng, W.T., Plante, A.F., Six, J., 2013. Improving estimates of maximal organic carbon stabilization by fine soil particles. *Biogeochemistry*, 112 (1–3), 81–93. https://doi.org/10.1007/s10533-011-9679-7

Francia, J.R., Zuazo, V.H.D., Raya, A.M., 2006. Environmental impact from mountainous olive orchards under different soil-management systems (SE Spain). *Science of the Total Environment*, *358*(1-3), 46-60. https://doi.org/10.1016/j.scitotenv.2005.05.036

Fernández-Hernández, A., Roig, A., Serramiá, N., Civantos, C.G.O., Sánchez-Monedero, M.A., 2014. Application of compost of two-phase olive mill waste on olive grove: Effects on soil, olive fruit and olive oil quality. *Waste Management*, *34*(7), 1139-1147. https://doi.org/10.1016/j.wasman.2014.03.027

Fernández-Romero, M.L., Lozano-García, B., Parras-Alcántara, L., 2014.Topography and land use change effects on the soil organic carbon stock of forest soils in Mediterranean natural areas. *Agriculture, Ecosystems and Environment* 195, 1-9. https://doi.org/10.1016/j.agee.2014.05.015

Fierer, N., Bradford, M.A., Jackson, R.B., 2007. Toward an ecological classification of soil bacteria. *Ecology*, 88 (6), 1354–1364. https://doi.org/10.1890/05-1839

Fissore, C., Dalzell, B.J., Berhe, A.A., Voegtle, M., Evans, M., Wu, A., 2017. Influence of topography on soil organic carbon dynamics in a Southern California grassland. *Catena*, *149*, 140-149. https://doi.org/10.1016/j.catena.2016.09.016

Fonte, S.J., Winsome, T., Six, J., 2009. Earthworm populations in relation to soil organic matter dynamics and management in California tomato cropping systems. *Applied soil ecology*, *41*(2), 206-214. https://doi.org/10.1016/j.apsoil.2008.10.010

Francaviglia, R., Ledda, L., Farina, R., 2018. Organic carbon and ecosystem services in agricultural soils of the Mediterranean Basin. In *Sustainable Agriculture Reviews,* 28 (pp. 183-210). Springer, Cham. https://doi.org/10.1007/978-3-319-90309-5_6

Franzluebbers, A.J., Arshad, M.A., 1997. Particulate organic carbon content and potential mineralization as affected by tillage and texture. *Soil Science Society of America Journal*, 61, 1382–1386. https://doi.org/10.2136/sssaj1997.03615995006100050014x

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., Zaehle, S., 2020. Global carbon budget 2020. *Earth System Science Data*, *12*(4), 3269-3340. https://doi.org/10.5194/essd-12-3269-2020

Gao, Z., Sasaki, K., Qiu, X., 2018. Structural memory effect of Mg–Al and Zn–Al layered double hydroxides in the presence of different natural humic acids: process and mechanism. *Langmuir*, 34, 5386–5395, 19. https://doi.org/10.1021/acs.langmuir.8b00059

García, R.R., Ochoa, V., Viñegla, B., Hinojosa, M.B., Peña, S.R., Liébanas, G., Linares, J.C., Carreira, J.A., 2009. Soil enzymes, nematode community and selected physico-chemical properties as soil quality indicators in organic and conventional olive oil farming: influence of seasonality and site features. *Applied Soil Ecology*, 41:305–314. https://doi.org/10.1016/j.apsoil.2008.12.004

Garcia-Franco, N., Walter, R., Wiesmeier, M., Hurtarte, L.C.C., Berauer, B.J., Buness, V., Kögel-Knabner, I., 2020. Biotic and abiotic controls on carbon storage in aggregates in calcareous alpine and prealpine grassland soils. *Biology and Fertility of Soils*, 1-16. https://doi.org/10.1007/s00374-020-01518-0

Gardi, C., Angelini, M., Barceló, S., Comerma, J., Cruz Gaistardo, C., Encina Rojas, A., … Vargas, R., 2014. Atlas de suelos de América Latina y el Caribe, Comisión Europea. *Oficina de Publicaciones de la Unión Europea, L-2995, Luxembourg*.

Garratt, M.P., Bommarco, R., Kleijn, D., Martin, E., Mortimer, S.R., Redlich, S., van Gils, S., 2018. Enhancing soil organic matter as a route to the ecological intensification of European arable systems. *Ecosystems, 21*(7), 1404-1415. https://doi.org/10.1007/s10021-018-0228-2

Garzon, I., 2006. Reforming the common agricultural policy: history of a paradigm change. Springer. https://doi.org/10.1057/9780230626577

Ghaley, B.B., Wosten, H., Olesen, J.E., Schelde, K., Baby, S., Karki, Y.K., Borgesen, C.D., Smith, P., Yeluripati, J., Ferrise, R., Bindi, M., Kuikman, P., Lesschen, J.P., Porter, J.R., 2018. Simulation of Soil Organic Carbon Effects on Long-Term Winter Wheat (*Triticum aestivum*) Production Under Varying Fertilizer Inputs. *Frontiers in plant science*, *9*, 1158. https://doi.org/10.3389/fpls.2018.01158.

Global Carbon Budget, 2019. Disponible online: https://www.globalcarbonproject.org/carbonbudget/archive/2019/GCP_CarbonBudget_2019.pdf

Global Carbon Budget, 2020. Disponible online: https://www.globalcarbonproject.org/carbonbudget/20/files/GCP_CarbonBudget_2020.pdf

Gocht, A., Ciaian, P., Bielza, M., Terres, J. M., Röder, N., Himics, M., Salputra, G., 2017. EU-wide economic and environmental impacts of CAP greening with high spatial and farm-type detail. *Journal of Agricultural Economics*, *68*(3), 651-681. https://doi.org/10.1111/1477-9552.12217

Gómez, J.A., Romero, P., Giráldez, J.V., Fereres, E., 2004. Experimental assessment of runoff and soil erosion in an olive grove on a Vertic soil in southern Spain as affected by soil management. *Soil Use and Management*, *20*(4), 426-431. https://doi.org/10.1111/j.1475-2743.2004.tb00392.x

Gómez, J.A., Sobrinho, T.A., Giráldez, J.V., Fereres, E., 2009b. Soil management effects on runoff, erosion and soil properties in an olive grove of Southern Spain. *Soila Tillage Research*, 102,5–13. https://doi.org/10.1016/j.still.2008.05.005

Gómez, J.A., Campos, M., Guzmán, G., Castillo-Llanque, F., Vanwalleghem, T., Lora, Á., Giráldez, J.V., 2018. Soil erosion control, plant diversity, and arthropod communities under heterogeneous cover crops in an olive orchard. *Environmental Science and Pollution Research*, 25(2), 977-989. https://doi.org/10.1007/s11356-016-8339-9

Gómez, J.A., Guzmán, M.G., Giráldez, J.V., Fereres, E., 2009a. The influence of cover crops and tillage on water and sediment yield, and on nutrient, and organic matter losses in an olive orchard on a sandy loam soil. *Soil and Tillage Research*, 106,137–144. https://doi.org/10.1016/j.still.2009.04.008

González-Rosado, M. Parras-Alcántara, L. Aguilera-Huertas, J. Benítez, C. Lozano-García, B., 2020a. Effects of land management change on soil aggregates and organic carbon in Mediterranean olive groves. *Catena*, 195, 104840. https://doi.org/10.1016/j.catena.2020.104840

González-Rosado, M. Parras-Alcántara, L. Aguilera-Huertas, J. Lozano-García, B., 2021. Long-term evaluation of the initiative 4‰ under different soil managements in Mediterranean olive groves. *Science of The Total Environment*, 758, 143591. https://doi.org/10.1016/j.scitotenv.2020.143591

González-Rosado, M., Lozano-García, B., Aguilera-Huertas, J., Parras-Alcántara, L., 2020b. Short-term effects of land management change linked to cover crop on soil organic carbon in Mediterranean olive grove hillsides. *Science of The Total Environment*, *744*, 140683. https://doi.org/10.1016/j.scitotenv.2020.140683

Graetz, H.A., 1997. Suelos y fertilización. 80 p. *FL Orozco, Trad. Trillas*, México. ISBN: 978-968-24-8387-5

Greer, A., 2017. Post-exceptional politics in agriculture: an examination of the 2013 CAP reform. *Journal of European Public Policy*, *24*(11), 1585-1603. https://doi.org/10.1080/13501763.2017.1334080

Guerra, A., 1994. The effect of organic matter content on soil erosion in simulated rainfall experiments in W. Sussex, UK. *Soil use and management*, *10*(2), 60-64. https://doi.org/10.1111/j.1475-2743.1994.tb00460.x

Hamkalo, Z., Bedernichek, T., 2014. Total, cold and hot water extractable organic carbon in soil profile: impact of land-use change. *Zemdirbyste-Agriculture*, 101(2), 125-132. https://doi.org/10.13080/Z-A.2014.101.016

Hassink, J., 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant Soil*, 191, 77–87. https://doi.org/10.1023/A:1004213929699

Haynes, R.J., Naidu, R., 1998. Influence of lime, fertiliser and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling in Agroecosystems*, *51*, 123–137. https://doi.org/10.1023/A:1009738307837

Hernández, A.J., Lacasta, C., Pastor, J., 2005. Effects of different management practices on soil conservation and soil water in a rainfed olive orchard. *Agricultural Water Management*, 77, 232–248. https://doi.org/10.1016/j.agwat.2004.09.030

Hobley, E., Wilson, B., Wilkie, A., Gray, J., Koen, T., 2015. Drivers of soil organic carbon storage and vertical distribution in Eastern Australia. *Plant Soil*, 390, 111–127. https://doi.org/10.1007/s11104-015-2380-1

Hobley, E.U., Baldock, J., Wilson, B., 2016. Environmental and human influences on organic carbon fractions down the soil profile. *Agriculture, Ecosystems & Environment*, 223, 152–166. https://doi.org/10.1016/j.agee.2016.03.004

Hoorman, J.J., Islam, R., 2010. Understanding Soil Microbes and Nutrient Recycling. Fact sheet SAG-16-10, The Ohio State University, Columbus, USA. Dsiponible en: https://ohioline.osu.edu/factsheet/SAG-16

Hristov, J., Clough, Y., Sahlin, U., Smith, H. G., Stjernman, M., Olsson, O., Brady, M.V., 2020. Impacts of the EU's Common Agricultural Policy "Greening" Reform on Agricultural Development, Biodiversity, and Ecosystem Services. *Applied Economic Perspectives and Policy*.
https://doi.org/10.1002/aepp.13037

Huntingford, C., Mercado, L., 2016. High chance that current atmospheric greenhouse concentrations commit to warmings greater than 1.5 Cover land. *Scientific Reports*, 6, 30294. https://doi.org/10.1038/srep30294

Hutchinson, J. J., Campbell, C. A., Desjardins, R. L., 2007. Some perspectives on carbon sequestration in agriculture. *Agricultural and forest meteorology*, *142*(2-4), 288-302. https://doi.org/10.1016/j.agrformet.2006.03.030

Iglesias, M.T., 2008. Estudio del carbono de la biomasa microbiana en suelos alterados. *Lazaroa*, *29*, 117. Disponible en: https://revistas.ucm.es/index.php/LAZA/article/download/LAZA0808110117A/8858/0

Infante-Amate J. Villa, I. Aguilera, E. Torremocha, E. Guzmán, G. Cid, A., 2016. The Making of Olive Landscapes in the South of Spain. A History of Continuous Expansion and Intensification. In: Agnoletti M., Emanueli F. (eds) Biocultural Diversity in Europe. Environmental History, vol 5. Springer, Cham. https://doi.org/10.1007/978-3-319-26315-1_8

Infante-Amate, J., 2014. ¿Quién levantó los olivos? Historia de la especialización olivarera en el sur de España (ss. XVIII–XX). Ministerio de Agricultura, Alimentación y Medio Ambiente. Madrid. ISBN: 978-8449114199

IPCC, 2014. *Climate Change 2014: Mitigation of Climate Change*. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2006. Directrices del IPCC de 2006 para los inventarios nacionales de gases de efecto invernadero. Volumen 4. Agricultura, silvicultura y otros usos de la tierra. Disponible en: https://www.ipcc-nggip.iges.or.jp/public/2006gl/spanish/

IPCC, 2018. Global Warming of 1.5 °C. Special Report Intergovernmental Panel on Climate Change. Disponible en: https://www.ipcc.ch/sr15/

IPCC, 2019. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Edited by P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson- Delmotte, H.-O. Pörtner, D. C. Roberts et al. Intergovernmental Panel of Climate Change. Disponible en: https://www.ipcc.ch/srccl/

Jackson, R. B., Le Quéré, C., Andrew, R. M., Canadell, J. G., Korsbakken, J. I., Liu, Z., Zheng, B., 2018. Global energy growth is outpacing decarbonization. *Environmental Research Letters*, *13*(12), 120401. https://doi.org/10.1088/1748-9326/aaf303

Jaiswal, B., Agrawal, M., 2019. Carbon footprints of agriculture sector. In Carbon footprints. *Environmental Footprints and Eco-design of Products and Processes*. 81–99. https://doi.org/10.1007/978-981-13-7916-1_4.

Jastrow, J.D., Boutton, T.W., Miller, R.M., 1996. Carbon dynamics of aggregate-associated organic matter estimated by carbon-13 natural abundance. *Soil Science Society of America Journal*. 60 (3), 801–807. https://doi.org/10.2136/sssaj1996.036159950 06000030017x

Jarecki, M.K., Lal, R., 2005. Soil organic carbon sequestration rates in two long-term no-till experiments in Ohio. *Soil Science*, *170*(4), 280-291.

Jian, J., Du, X., Reiter, M. S., Stewart, R. D., 2020. A meta-analysis of global cropland soil carbon changes due to cover cropping. *Soil Biology and Biochemistry*, *143*, 107735. https://doi.org/10.1016/j.soilbio.2020.107735

Jobbagy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*,*10* (2), 423–436. https://doi.org/10.1890/1051-0761(2000)010[0423:TVDOSO] 2.0.CO;2

Junta de Andalucía, 2015. Plan director del olivar andaluz. Consejería de Agricultura, Pesca y Desarrollo Rural. Disponible en: https://www.juntadeandalucia.es/export/drupaljda/Plan%20Director%20del%20Olivar.pdf

Junta de Andalucía, 2017. Costes en explotaciones de olivar. Campaña 2015/16. Consejería de Agricultura, Pesca y Desarrollo Rural. Disponible en : https://www.juntadeandalucia.es/export/ drupaljda/estudios_informes/18/01/Costes_en_explotaciones_de_olivar.pdf

Kabiri, V., Raiesi, F., Ghazavi, M.A., 2015. Six years of different tillage systems affected aggregate-associated SOM in a semi-arid loam soil from Central Iran. *Soil Tillage Research*, 154:114–125. https://doi.org/10.1016/j.still.2015.06.019

Kairis, O., C. Karavitis, A. Kounalaki, L. Salvati, and C. Kosmas. 2013. The Effect of Land Management Practices on Soil Erosion and Land Desertification in an Olive Grove. *Soil Use and Management*, 29: 597–606 (3). https://doi.org/10.1111/sum.12074

Kalbitz, K., Solinger, S., Park, J. H., Michalzik, B., Matzner, E., 2000. Controls on the dynamics of dissolved organic matter in soils: a review. *Soil science*, 165(4), 277-304.

Kallenbach, C.M., Frey, S.D., Grandy, A.S., 2016. Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. *Nature Communications*, 7, 13630. https://doi.org/10.1038/ncomms13630

Kan, Z.R., Virk, A.L., He, C., Liu, Q.Y., Qi, J.Y., Dang, Y.P., Zhang, H.L., 2020. Characteristics of carbon mineralization and accumulation under long-term conservation tillage. *Catena*, *193*, 104636. https://doi.org/10.1016/j.catena.2020.104636

Kane, D. 2015. Carbon Sequestration Potential on Agricultural Lands: A Review of Current Science and Available Practices. Scholes R.J. & Noble I.R. 2001. Storing C on land. *Science* 294:1012–1013.

Kasel, S., Bennett, L.T., 2007. Land-use history, forest conversion, and soil organic carbon in pine plantations and native forests of south eastern Australia. *Geoderma*, 137, 401–413. https://doi.org/10.1016/j.geoderma.2006.09.002

Kätterer, T., Bolinder, M.A., Andren, O., Kirchmann, H., Menichetti, L., 2011. Roots contribute more to refractory soil organic matter than above-ground crop residues, as revealed by a long-term field experiment. *Agriculture*, *Ecosystems & Environment*. 141 (1–2), 184–192. http://dx.doi.org/10.1016/j.agee.2011.02.029

Kavvadias, V., Koubouris, G., 2019. Sustainable Soil Management Practices in Olive Groves. In: Panpatte D., Jhala Y. (eds) Soil Fertility Management for Sustainable Development. Springer, Singapore. https://doi.org/10.1007/978-981-13-5904-0_8

Kaye, J.P., Quemada, M., 2017. Using cover crops to mitigate and adapt to climate change. A review. *Agronomy for sustainable development*, *37*(1), 4. https://doi.org/10.1007/s13593-016-0410-x

Khalid, S., Khan, H.A., Arif, M., Altawaha, A.R., Adnan, M., Fahad, S., Parmar, B., 2019. Organic matter management in cereals based system: Symbiosis for improving crop productivity and soil health. In *Sustainable Agriculture Reviews*, 29 (pp. 67-92). Springer, Cham. https://doi.org/10.1007/978-3-030-26265-5_3

Kopittke, P.M., Menzies, N.W., Wang, P., McKeena, B.A., Lombi, E., 2019. Soil and the intensification of agriculture for global food security. *Environment International*, 132, 105078. https://doi.org/10.1016/j.envint.2019.105078.

Koven, C.D., Hugelius, G., Lawrence, D.M., Wieder, W.R., 2017. Higher climatological temperature sensitivity of soil carbon in cold than warm climates. *Nature Climate Change*, 7, 817–822. https://doi.org/10.1038/nclimate3421

Kravchenko, A.N., Negassa, W.C., Guber, A.K., Rivers, M.L., 2015. Protection of soil carbon within macro-aggregates depends on intra-aggregate pore characteristics. *Scientific Repots*, 5,16261. https://doi.org/10.1038/srep16261

Kuhn, N.J., 2007. Erodibility of soil organic matter: independence of organic matter resistant to interrill erosion. *Earth Surface Processes and Landforms*, *32*, 794–802. https://doi.org/10.1002/esp.1486

Kunkel, M.L., Flores, A.N., Smith, T.J., McNamara, J.P., Benner, S.G., 2011. A simplified approach for estimating soil carbon and nitrogen stocks in semi-arid complex terrain. *Geoderma*, 165(1), 1-11. https://doi.org/10.1016/j.geoderma.2011.06.011

Ladoni, M., Basir, A., Kravchenko, A., 2015. Which soil carbon fraction is the best for assessing management differences? A statistical power perspective. *Soil Science Society of America Journal*, 79 (3), 848-857. https://doi.org/10.2136/sssaj2014.10.0426

Lal, R., 2003. Soil erosion and the global carbon budget. *Environment International*, 29, 437–450. https://doi.org/10.1016/S0160-4120(02)00192-7

Lal, R., 2004a. Soil carbon sequestration impacts on global climate change and food security. *Science*, 304:1623–1627. https://doi.rg/10.1126/science.1097396

Lal, R., 2004b. Soil carbon sequestration to mitigate climate change. *Geoderma*, 123:1–22. https://doi.org/10.1016/j.geoderma.2004.01.032

Lal, R., 2008. Carbon sequestration. Philosophical Transactions of the Royal Society, 363, 815–830. https://doi.org/10.1098/rstb.2007.2185

Lal, R., 2010. Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. *Bioscience*, 60, 708–721. https://doi.org/10.1525/bio.2010.60.9.8

Lal, R.., 2016. Soil health and carbon management. *Food and Energy Security*, *5*(4), 212-222. https://doi.org/10.1002/fes3.96

Lal, R., 2018. Digging deeper: a holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. *Global Change Biology*, 24, 3 285–301. https://doi.org/10.1111/gcb.14054

Lal, R., 2019a. Accelerated soil erosion as a source of atmospheric CO2. *Soil and Tillage Research*, 188, 35-40. https://doi.org/10.1016/j.still.2018.02.001

Lal, R., 2019b. Promoting "4 Per Thousand" and "Adapting African Agriculture" by south-south cooperation: Conservation agriculture and sustainable intensification. *Soil Tillage Research*, 188, 27-34. https://doi.org/10.1016/j.still.2017.12.015

Lal, R., 2020a. Food security impacts of the "4 per Thousand" initiative. *Geoderma*, *374*, 114427. https://doi.org/10.1016/j.geoderma.2020.114427

Lal, R., 2020b. Soil Erosion and Gaseous Emissions. *Applied Sciences*, 10 (8), 2784. https://doi.org/10.3390/app10082784

Laurence, W.F., 2019. Anthropocene. *Current Biology*, 29, R953–R954. https://doi.org/10.1016/j.cub.2019.07.055.

Lavallee, J. M., Soong, J. L., Cotrufo, M. F., 2020. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Global Change Biology*, 26 (1), 261-273. https://doi.org/10.1111/gcb.14859

Le Foll, S., 2015. Agriculture intelligente face au climat. Intervention de Stéphane Le Foll 2015 à Montpellier à l´occasion de la conference COP21. Disponible en: https://agriculture.gouv.fr/telecharger/71763?token=655d1ccd87f92f75c8543a7e685ca7591ec0f522d6fcfd025e1265fcc6bfae3d

Le Quéré, C., Andrew, R. M., Friedlingestein, P., Stich, D., Pongratz, J., Manning, A. C., Zhu, D., 2017. Global carbon budget 2017. *Earth System Science Data*, *8*(2), 605–649. https://doi.org/10.5194/essd-2017-123

Le Quéré, C., Jackson, R. B., Jones, M. W., Smith, A. J., Abernethy, S., Andrew, R. M., ... & Peters, G. P., 2020. Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement. *Nature Climate Change*, 1-7. https://doi.org/10.1038/s41558-020-0797-x

Ledo, A., Smith, P., Zerihun, A., Whitaker, J., Vicente Vicente, J., Qin, Z., Mcnamara, N., Zinn, Y., Llorente, M., Liebig, M., Kuhnert, M., Dondini, M., Don, A., Diaz-Pines, E., Datta, A., Bakka, H., Aguilera, E., Hillier, J., 2020. Changes in soil organic carbon under perennial crops. *Global Change Biology*, 26 (7). https://doi.org/10.1111/gcb.15120

Lefèvre, C., Rekik, F., Alcantara, V., Wiese, L., 2017. Carbono Orgánico del Suelo: el potencial oculto. Disponible online: http://www.fao.org/3/b-i6937s.pdf

Liang, C., Schimel, J.P., Jastrow, J.D., 2017. The importance of anabolism in microbial control over soil carbon storage. *Nature microbiology*, 2(8), 1-6. https://doi.org/10.1038/nmicrobiol.2017.105

López-Bellido, R.J., Muñoz-Romero, V., Fuentes-Guerra, R., Fernández-García, P., López-Bellido, L., 2017. No-till: A key tool for sequestering C and N in microaggregates on a Mediterranean Vertisol. *Soil and Tillage Research*, 166, 131-137. https://doi.org/10.1016/j.still.2016.09.012

López-Fando, C., Pardo, M.T., 2009. Changes in soil chemical characteristics with different tillage practices in a semi-arid environment. *Soil and Tillage Research* 104, 278-284. https://doi.org/10.1016/j.still.2009.03.005

López-Vicente, M., Calvo-Seas, E., Álvarez, S., Cerdà, A., 2020. Effectiveness of cover crops to reduce loss of soil organic matter in a rainfed vineyard. *Land*, 9(7), 230. https://doi.org/10.3390/land9070230

Lozano-García, B., Parras-Alcántara, L., del Toro, M., 2011. The effects of agricultural management with oil mill by-products on surface soil properties, runoff and soil losses in southern Spain. *Catena*, 85, 187–193. https://doi.org/10.1016/j.catena.2011.01.017

Lozano-García, B., Francaviglia, R., Renzi, G., Benítez, C., González-Rosado, M., Parras-Alcántara, L.,2020. Land use change effects on soil organic carbon store. An opportunity to soils regeneration in Mediterranean areas: Implications in the 4p1000 notion. Ecological indicators, 119, 106831. https://doi.org/10.1016/j.ecolind.2020.106831

Lugato, E., Paustian, K., Pangos, P., Jones, A., Borrelli, P., 2016. Quantifying the erosion effect on current carbon budget of European agricultural soils at high spatial resolution. *Global Change Biology*. 22, 1976–1984. https://doi.org/10.1111/gcb.13198

Ma, S.T., Zhao, X., Chao, P., Liu, Y., Lal, R., Xue, J.F., Zhang, H.L., 2018. Enhancing soil organic carbon by managing nitrogen in China. *In* Soil Nitrogen Uses and Environmental Impacts, eds. R. Lal and B.A. Stewart, 231-254. Boca Raton: CRC Press.

Mabit, L., Chhem-Kieth, S., Toloza, A., Vanwalleghem, T., Bernard, C., Amate, J.I., González de Molina, M., Gómez, J.A., 2012. Radioisotopic and physicochemical background indicators to assess soil degradation affecting olive orchards in southern Spain. *Agriculture, Ecosystems & Environment. 159*, 70–80. https://doi.org/10.1016/j.agee.2012.06.014

Madejón, P., Domínguez, M.T., Díaz, M.J., Madejón, E., 2016. Improving sustainability in the remediation of contaminated soils by the use of compost and energy valorization by Paulownia fortune. *Science of the Total Environment* 539, 401-409. http://dx.doi.org/10.1016/j.scitotenv.2015.09.018

Malhi, Y., 2017. The concept of the Anthropocene. *Annual Reviews*. 42, 77–104. https://doi.org/10.1146/annurev-environ-102016060854

MAPA. 2018. Encuesta sobre superficies y rendimientos de cultivos. Análisis de las técnicas de mantenimiento del suelo y de los métodos de siembra en España. Ministerio de Agricultura, Pesca y Alimentación. Madrid. Available in https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/cubiertas2018_tcm30-504664.pdf

Martin, M., Wattenbach, M., Smith, P., Meersmans, J., Jolivet, C., Boulonne, L., Arrouays, D., 2011. Spatial distribution of soil organic carbon stocks in France. *Biogeosciences*, *8*(5), 1053-1065. https://doi.org/10.5194/bg-8-1053-2011

Martinez-Mena, M., Lopez, J., Almagro, M., Albaladejo, J., Castillo, V., Ortiz, R., Fayos, B., 2008. Effect of water erosion and cultivation on the soil carbon stock in a semiarid area of South-East Spain. *Soil and Tillage Research*, 99, 119–129. https://doi.org/10.1016/j.still.2008.01.009

Martínez-Mena, M., Almagro, M., García-Franco, N., Vente, J. D., García, E., Boix-Fayos, C., 2019. Fluvial sedimentary deposits as carbon sinks: organic carbon pools and stabilization mechanisms across a Mediterranean catchment. *Biogeosciences*, *16*(5), 1035-1051. https://doi.org/10.5194/bg-16-1035-2019

Mayes, M., Marin-Spiotta, E., Szymanski, L., Erdoğan, M.A., Ozdoğan, M., Clayton, M., 2014. Soil type mediates effects of land use on soil carbon and nitrogen in the Konya Basin, Turkey. *Geoderma*, *232*, 517-527. https://doi.org/10.1016/j.geoderma.2014.06.002

MEA, 2005. Millennium Ecosystem Assessment: Ecosystems and Human Well-being: Synthesis. Island Press, Washington DC.

Mikutta, R., Kleber, M., Torn, M.S., Jahn, R., 2006. Stabilization of soil organic matter: association with minerals or chemical recalcitrance? *Biogeochemistry*. 77 (1), 25–56. https://doi.org/10.1007/s10533-005-0712-6

Milori, D.M.B.P., Martin-Neto, L., Bayer, C., Mielniczuk, J., Bagnato, V.S., 2002. Humification degree of soil Humic acids determined by fluorescence spectroscopy. *Soil Science*, 167, 739–749. https://doi.org/10.1097/00010694-200211000-00004.

Minasny, B., Malone, B.P., McBratney, A.B., Angers Dominique Arrouays, D.A., Chambers, A., Chaplot, V., Chen, Z., Chengg, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Young Hong, S., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, Ch., Vågen, T.G., van-Wesemael, B., Winowiecki, L., 2017. Soil carbon 4 per mille. *Geoderma*, *292*, 59-86. https://doi.org/10.1016/j.geoderma.2017.01.002

Minasny, B., McBratney, A.B., Malone, B.P., Wheeler, I., 2013. Digital mapping of soil carbon. In: Sparks, D.L. (Ed.), Advances in Agronomy. vol. 118. Elsevier Academic Press Inc, San Diego, pp. 1–47. https://doi.org/10.1016/B978-0-12-405942-9.00001-3

Mitchell, P.J., Simpson, A.J., Soong, R., Simpson, M.J., 2015. Shifts in microbial community and water-extractable organic matter composition with biochar amendment in a temperate forest soil. *Soil Biology and Biochemistry*, *81*, 244-254. https://doi.org/10.1016/j.soilbio.2014.11.017

Montanarella, L., 2015. Agricultural policy: Govern our soils. *Nature News*, *528* ,7580, 32. https://doi.org/10.1038/528032a

Montanarella, L., Panagos, P., 2020. The relevance of sustainable soil management within the European Green Deal, Land Use Policy, Volume 100, 2021, 104950, ISSN 0264-8377, https://doi.org/10.1016/j.landusepol.2020.104950.

Montanaro, G., Nuzzo, V., Xiloyannis, C., Dichio. B., 2018. Climate change mitigation and adaptation in agriculture: the case of the olive. *Journal of Water and Climate Change* 1; 9 (4): 633–642. https://doi.org/10.2166/wcc.2018.023

Mora, P., Miambi, E., Jimenez, J.J., Decaens, T., Rouland, C., 2005. Functional complement of biogenic structures produced by earthworms, termites and ants in the neotropical savannas. *Soil Biology and Biochemistry*. *37*, 1043–1048. https://doi.org/10.1016/j.soilbio.2004.10.019

Moreno-García, M., Repullo-Ruibérriz de Torres, M. A., Carbonell-Bojollo, R. M., Ordoñez-Fernández, R., 2018. Management of pruning residues for soil protection in olive orchards. *Land Degradation & Development*, 29, 2975-2984. https://doi.org/10.1002/ldr.3054

Morugán-Coronado, A., Linares, C., Gómez-López, M.D., Faz, A., Zornoza, R., 2020. The impact of intercropping, tillage and fertilizer type on soil and crop yield in fruit orchards under Mediterranean conditions: A meta-analysis of field studies. *Agricultural Systems*, *178*, 102736. https://doi.org/10.1016/j.agsy.2019.102736

Müller-Nedebock, D., Chaplot, V., 2015. Soil carbon losses by sheet erosion: a potentially critical contribution to the global carbon cycle. *Earth Surface Processes and Landforms*, *40*(13), 1803-1813. 178. https://doi.org/10.1016/j.agsy.2019.102736.

Muñoz-Rojas, M., Abd-Elmabod, S.K., Zavala, L.M., De la Rosa, D., Jordán, A., 2017. Climate change impacts on soil organic carbon stocks of Mediterranean agricultural areas: a case study in Northern Egypt. *Agriculture, Ecosystems & Environment*. 238, 142–152. https://doi.org/10.1016/j.agee.2016.09.001

Neff, J.C., Asner, G.P., 2001. Dissolved organic carbon in terrestrial ecosystems: synthesis and a model. *Ecosystems*, *4*(1), 29-48. https://doi.org/10.1007/s100210000058

Novara, A., Gristina, L., Sala, G., Galati, A., Crescimanno, M., Cerdà, A., La Mantia, T., 2017. Agricultural land abandonment in Mediterranean environment provides ecosystem services via soil carbon sequestration. *Science of the Total Environment*, *576*, 420-429. https://doi.org/10.1016/j.scitotenv.2016.10.123

Obalum, S. E., Chibuike, G. U., Peth, S., Ouyang, Y., 2017. Soil organic matter as sole indicator of soil degradation. *Environmental monitoring and assessment*, *189*(4), 176. https://doi.org/10.1007/s10661-017-5881-y

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F. Erasmi, S., 2016.Greenhouse gas emissions from soils—a review. *Geochemistry*. 76, 327–352. https://doi.org/10.1016/j.chemer.2016.04.002

Ojeda-Rivera, J. F., Andreu-Lara, C., Infante-Amate, J. (2018). Razones y recelos de un reconocimiento patrimonial: los paisajes del olivar andaluz. *Boletín De La Asociación De Geógrafos Españoles*, (79). https://doi.org/10.21138/bage.2471

Oldfield, E. E., Wood, S. A., Bradford, M. A., 2018. Direct effects of soil organic matter on productivity mirror those observed with organic amendments. *Plant and soil*, *423*(1-2), 363-373.

Oldfield, E., Bradford, M., Wood, S., 2019. Global meta-analysis of the relationship between soil organic matter and crop yields. Soil 5, 15–32. https://doi.org/10.5194/soil-5-15-2019.

Olson, K.R., Al-Kaisi, M.M., Lal, R., Lowery, B., 2014. Experimental consideration, treatments, and methods in determining soil organic carbon sequestration rates. *Soil Science Society of America Journal*, *78*(2), 348-360. https://doi.org/10.2136/sssaj2013.09.0412

Ordóñez, R., González, P., Pastor, M., 2007a. Cubiertas inertes: Los restos de poda como protección y mejora de las propiedades del suelo. In A. Rodríguez-Lizana, R. Ordoñez-Fernández, J. Gil-Ribes (Eds.), *Cubiertas vegetales en olivar* (pp. 159–168). Junta de Andalucía.

Ordóñez-Fernández, R., Rodríguez-Lizana, A., Espejo-Pérez, A. J., González-Fernández, P., Saavedra, M. M., 2007b. Soil and available phosphorus losses in ecological olive groves. *European journal of agronomy*, *27*(1), 144-153. https://doi.org/10.1016/j.eja.2007.02.006

Ouyang, W., Wu, Y., Hao, Z., Zhang, Q., Bu, Q., Gao, X., 2018. Combined impacts of land use and soil property changes on soil erosion in a mollisol area under long-term agricultural development. *Science of the total environment*, *613*, 798-809. https://doi.org/10.1016/j.scitotenv.2017.09.173

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., van Ypserle, J. P., 2014. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change (p.151). Disponible en: https://www.ipcc.ch/report/ar5/syr/

Palese, A. M., Vignozzi, N., Celano, G., Agnelli, A. E., Pagliai, M., Xiloyannis, C., 2014. Influence of soil management on soil physical characteristics and water storage in a mature rainfed olive orchard. *Soil and Tillage Research*, *144*, 96-109. https://doi.org/10.1016/j.still.2014.07.010

Panagos, P., Meusburger, K., Ballabio, C., Borrelli, P., Alewell, C., 2014. Soil erodibility in Europe: A high-resolution dataset based on LUCAS. *Science of the total environment*. *479*, 189-200. https://doi.org/10.1016/j.scitotenv.2014.02.010

Parras-Alcántara, L., Díaz, J.L., Lozano-García, B., 2013. Organic farming affects C and N in soils under olive groves in Mediterranean areas. Land Degrad Dev 26:800–806. https://doi.org/10.1002/ldr.2231

Parras-Alcántara, L., Lozano-García, B., 2014. Conventional tillage vs. organic farming in relation to soil organic carbon stock in olive groves in Mediterranean rangelands (southern Spain). *Solid Earth Discuss* 6:35–70. https://doi.org/10.5194/sed-6-35-2014

Parras-Alcántara, L., Lozano-García, B., Galán-Espejo, A., 2015. Soil organic carbon along an altitudinal gradient in the Despeñaperros Natural Park, southern Spain. *Solid Earth* 6, 125–134. https://doi.org/10.5194/se-6-125-2015.

Parras-Alcantara, L., Lozano-Garcia, B., Keesstra, S., Cerda, A., Brevik, E.C., 2016. Long-term effects of soil management on ecosystem services and soil loss estimation in olive grove top soils. *Science of the total environment*. 571, 498–506. https://doi.org/10. 1016/j.scitotenv.2016.07.016

Pastor, M., 2008. Sistemas de manejo del suelo [Soil management systems]. In: Barranco D, Fernández-Escobar R, Rallo L (eds) El cultivo del olivo, 6ª edn. Junta de Andalucía, Consejería de Agricultura y Pesca & Ediciones. Mundi-Prensa, Madrid, pp. 239–295

Pastor, M., Castro, J., Vega, V., Humanes, M.D., 2001. Sistemas de manejo del suelo. En *El cultivo del olivo*, Barranco D, Fernandez-Escobar R, Rallo L (eds). Mundi Prensa: Madrid; 198–228.

Paul, E., 2014. Soil microbiology, ecology and biochemistry. Academic Press. pp. 598. https://doi.org/10.1016/C2011-0-05497-2

Paul, E.A., Collins, H.P., Leavitt, S.W., 2001. Dynamics of resistant soil carbon of Midwestern agricultural soils measured by naturally occurring 14 C abundance. *Geoderma*. 104, 239–256. https://doi.org/10.1016/S0016-7061(01)00083-0.

Paustian, K., Six, J., Elliott, E.T., Hunt, H.W., 2000. Management options for reducing CO2 emissions from agricultural soils. *Biogeochemistry* 48, 147–163. https://doi.org/10.1023/A:1006271331703

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., Smith, P., 2016. Climate-smart soils. *Nature*, *532*(7597), 49-57. https://doi.org/10.1038/nature17174

Peigné, J., Vian, J. F., Payet, V., & Saby, N. P. (2018). Soil fertility after 10 years of conservation tillage in organic farming. *Soil and Tillage Research*, *175*, 194-204. https://doi.org/10.1016/j.still.2017.09.008

Pereira, P., Barceló, D., Panagos, P.,2020. Soil and water threats in a changing environment. *Environmental Research*. *186*, 109501. https://doi.org/10.1016/j.envres.2020.109501

Peters, G. P., Andrew, R. M., Canadell, J. G., Friedlingstein, P., Jackson, R. B., Korsbakken, J. I., ... & Peregon, A., 2020. Carbon dioxide emissions continue to grow amidst slowly emerging climate policies. *Nature Climate Change*, *10*(1), 3-6. https://doi.org/10.1038/s41558-019-0659-6

Plante, A. F., I. Virto, and S. S. Malhi. 2010. Pedogenic, mineralogical and land-use controls on organic carbon stabilization in two contrasting soils. Canadian Journal of Soil Science *90* (15–26). https://doi.org/10.4141/CJSS09052

Plaza-Bonilla, D., Cantero-Martínez, C., Álvaro-Fuentes, J., 2010. Tillage effects on soil aggregation and soil organic carbon profile distribution under Mediterranean semi-arid conditions. *Soil Use and Management*, *26*(4), 465-474. https://doi.org/10.1111/j.1475-2743.2010.00298.x

Pleguezuelo, C.R.R., Durán-Zuazo, V.H., Martínez, J.R.F., 2018. Organic olive farming in Andalusia, Spain. A review. *Agronomy for Sustainable Development*. *38***,** 20. https://doi.org/10.1007/s13593-018-0498-2

Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemael, B. A. S., Schumacher, J., Gensior, A., 2011. Temporal dynamics of soil organic carbon after land-use change in the temperate zone–carbon response functions as a model approach. *Global Change Biology*, *17*(7), 2415-2427. https://doi.org/10.1111/j.1365-2486.2011.02408.x

Poulton, P., Johnston, J., Macdonald, A., White, R., Powlson, D., 2018. Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: evidence from long-term experiments at Rothamsted research, United Kingdom. *Global Change Biology* 24 (6), 2563–2584. https://doi.org/10.1111/gcb.14066.

Powlson, D., Whitemore, A., Goulding, K., 2011. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. *European Journal of Soil Science*, 62:42–45. https://doi.org/10.1111/j.1365-2389.2010.01342.x

Pribyl, D. W., 2010. A critical review of the conventional SOC to SOM conversion factor. *Geoderma*, *156*(3-4), 75-83. https://doi.org/10.1016/j.geoderma.2010.02.003

Pries, C.E.H., Castanha, C., Porras, R.C., Torn, M.S., 2017. The whole-soil carbon flux in response to warming. *Science*, *355*(6332), 1420-1423. https://doi.org/10.1126/science.aal1319

Proietti, S., Sdringola, P., Desideri, U., Zepparelli, F., Brunori, A., Ilarioni, L., Nasini, L., Regni, L., Proietti, P., 2014. Carbon footprint of an olive tree grove. *Applied Energy 127*:115–124. https://doi.org/10.1016/j.apenergy.2014.04.019

Pronk, G.J., Heister, K., Ding, G.C., Smalla, K., Kögel-Knabner, I., 2012b. Development of biogeochemical interfaces in an artificial soil incubation experiment; aggregation and formation of organo-mineral associations. *Geoderma* 189, 585–594. https://doi.org/10.1016/j.geoderma.2012.05.020

Qi, F., Kuppusamy, S., Naidu, R., Bolan, N.S., Ok, Y.S., Lamb, D., Li, Y., Yu, L., Semple, K. T., Wang, H., 2017. Pyrogenic carbon and its role in contaminant immobilization in soils. *Critical Review in Environmental Science and Technology*, *47*, 795–876. https://doi.org/10.1080/10643389.2017.1328918

Raiesi, F., Kabiri, V., 2017. Carbon and nitrogen mineralization kinetics as affected by tillage systems in a calcareous loam soil. *Ecological Engineering*, *106*, 24-34. https://doi.org/10.1016/j.ecoleng.2017.05.023

Rakić, T., Quartacci, M. F., Cardelli, R., Navari-Izzo, F., Stevanović, B., 2009. Soil properties and their effect on water and mineral status of resurrection Ramonda serbica. *Plant ecology*, *203*(1), 13-21. https://doi.org/10.1007/s11258-008-9498-7

Ramesh, T., Bolan, N. S., Kirkham, M. B., Wijesekara, H., Kanchikerimath, M., Rao, C. S., Wang, H., 2019. Soil organic carbon dynamics: Impact of land use changes and management practices: A review. *Advances in Agronomy* (Vol. 156, pp. 1-107). Academic Press. https://doi.org/10.1016/bs.agron.2019.02.001

Ramos, F.T., Dores, E.F.D.C., Weber, O.L.D.S., Beber, D.C., Campelo Jr, J.H., Maia, J.C.D.S., 2018. Soil organic matter doubles the cation exchange capacity of tropical soil under no-till farming in Brazil. *Journal of the Science of Food and Agriculture*, *98*(9), 3595-3602. https://doi.org/10.1002/jsfa.8881.

Recanati, F., Maughan, C., Pedrotti, M., Katarzyna, D., Marta., A., 2018. Assessing the role of CAP for more sustainable and healthier food systems in Europe: A literature review. *Science of The Total Environment*, 653. https://doi.org/10.1016/j.scitotenv.2018.10.3 77

Ren, W., Tian, H.Q., Tao, B., Huang, Y., Pan, S.F., 2012. China's crop productivity and soil carbon storage as influenced by multifactor global change. *Global Change Biology*. 18, 2945–2957. https://doi.org/10.1111/j.1365-2486.2012.02741.x

Repullo, M. A., Carbonell, R., Hidalgo, J., Rodríguez-Lizana, A., Ordóñez, R., 2012. Using olive pruning residues to cover soil and improve fertility. *Soil and Tillage Research*, *124*, 36-46. https://doi.org/10.1016/j.still.2012.04.003

Repullo-Ruibérriz de Torres, M. A., Fernández, R. M. O., García, J. M., García, M. M., Bojollo, R. M. C., 2014. Eficiencia de cubiertas vegetales de gramíneas, crucíferas y leguminosas para reducir la erosión y la pérdida de materia orgánica del suelo en olivar. *Agricultura de conservación: AC*, (*28*), 18-28.

Repullo-Ruibérriz de Torres, M. A., Ordóñez-Fernández, R., Giráldez, J. V., Márquez-García, J., Laguna, A., Carbonell-Bojollo, R., 2018. Efficiency of four different seeded plants and native vegetation as cover crops in the control of soil and carbon losses by water erosion in olive orchards. *Land Degradation & Development*, *29*(8), 2278-2290.https://doi.org/10.1002/ldr.3023

Reynaldo, V., Banwart, S., Black, H., Ingram, J., Joosten, H., Milne, E., Noellemeyer, E., 2012. The benefits of soil carbon. UNEP Yearbook 2012:19–33

Ribeiro Filho, A.A., Adams, C., Manfredini, S., Aguilar, R., Neves, W.A., 2015. Dynamics of soil chemical properties in shifting cultivation systems in the tropics: a meta-analysis. *Soil Use and Management*, *31*(4), 474-482. https://doi.org/10.1111/sum. 12224

Rodrigo-Comino, J., Giménez-Morera, A., Panagos, P., Pourghasemi, H. R., Pulido, M., Cerdà, A., 2020. The potential of straw mulch as a nature-based solution for soil erosion in olive plantation treated with glyphosate: A biophysical and socioeconomic assessment. *Land Degradation & Development*, *31*(15), 1877-1889. https://doi.org/10.1002/ldr.3305

Rodrigo-Comino, J., Taguas, E., Seeger, M., Ries, J. B., 2018. Quantification of soil and water losses in an extensive olive orchard catchment in Southern Spain. *Journal of Hydrology*, *556*, 749-758. https://doi.org/10.1016/j.jhydrol.2017.12.014

Rodríguez-Lizana, A., Espejo-Pérez, A. J., González-Fernández, P., Ordóñez-Fernández, R., 2008. Pruning residues as an alternative to traditional tillage to reduce erosion and pollutant dispersion in olive groves. *Water, Air, and Soil Pollution*, *193*(1-4), 165-173. https://doi.org/10.1007/s11270-008-9680-5

Rodríguez-Sousa, A.A., Barandica, J.M., Rescia, A.J., 2019. Estimation of Soil Loss Tolerance in Olive Groves as an Indicator of Sustainability: The Case of the Estepa Region (Andalusia, Spain). *Agronomy*, 9(12), 785. https://doi.org/10.3390/agronomy9120785

Rumpel, C., Chabbi, A., Nunan, N., Dignac, M.F., 2009. Impact of land use change on the molecular composition of soil organic matter. *Journal of Analytical and Applied Pyrolysis*, *85*:431–434. https://doi.org/10.1016/j.jaap.2008.10.011

Rumpel, C., Amiraslani, F., Chenu, C., Cardenas, M.G., Kaonga, M., Koutika, L.S., Soudi, B., 2020. The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. *Ambio*, *49* (1), 350-360. https://doi.org/10.1007/s13280-019-01165-2

Sánchez, M.S., Castro, J., Alonso, P.E., Alonso, P.J.L., García, B.J.M., Talavera, M., Durán-Zuazo, V.H., 2015. Tillage and herbicide decrease soil biodiversity in olive orchards. *Agronomy for Sustainable Development*. 35:691–700. https://doi.org/10.1007/s13593-014-0266-x

Sarker, J. R., Singh, B. P., Fang, Y., Cowie, A. L., Dougherty, W. J., Collins, D., Singh, B. K., 2019. Tillage history and crop residue input enhanced native carbon mineralisation and nutrient supply in contrasting soils under long-term farming systems. *Soil and Tillage Research*, 193, 71-84. https://doi.org/10.1016/j.still.2019.05.027

Sastre, B., Barbero-Sierra, C., Bienes, R., Marques, M. J., García-Díaz, A., 2017. Soil loss in an olive grove in Central Spain under cover crops and tillage treatments, and farmer perceptions. *Journal of Soils and Sediments*, 17*(*3), 873-888. https://doi.org/10.1007/s11368-016-1589-9

Sastre, B., Bienes, R., García-Díaz, A., 2018a. How much is soil volumetric water content influenced by cover crops in an olive grove in central Spain? *Acta Horticulturae*, 1199, 345–350. https://doi.org/10.17660/ActaHortic.2018.1199.54.

Sastre, B., Marques, M.J., García-Díaz, A., Bienes, R., 2018b. Three years of management with cover crops protecting sloping olive groves soils, carbon and water effects on gypsiferous soil. *Catena 171*, 115-124. https://doi.org/10.1016/j.catena.2018.07.003

Schulp, C.J.E., Nabulars, G.J., Verburg, P.H., de Waal, R.W., 2008. Effect of tree species on carbon stocks in forest floor and mineral soil and implications for soil carbon inventories. *Forest Ecology and Management, 256* (3), 482–490. https://doi.org/10.1016/j.foreco.2008.05.007

Scowcroft, P., Turner, D.R., Vitousek, P.M., 2008. Decomposition of Metrosideros polymorpha leaf litter along elevational gradients in Hawaii. *Global Change Biology*, 6, 73–85. https://doi.org/10.1046/j.1365-2486.2000.00282.x.

Shi, P., Schulin, R., 2018. Erosion-induced losses of carbon, nitrogen, phosphorus and heavy metals from agricultural soils of contrasting organic matter management. *Science of the Total Environment*, *618*, 210-218. https://doi.org/10.1016/j.scitotenv.2017.11.060

Simpson, A.J., Song, G., Smith, E., Lam, B., Novotny, E. H., Hayes, M.H.B., 2007. Unraveling the Structural components of soil humin by use of solution-state nuclear magnetic resonance spectroscopy. *Environmental Science & Technology*, 41, 876-883. https://doi.org/10.1021/es061576c

Six, J., Bossuyt, H., Degryze, S., Denief, K., 2004. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil & Tillage Research*, *79*, 7–31. https://doi.org/10.1016/j.still.2004.03.008

Six, J., Conant, R., Paul, E., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation. *Plant and Soil*, *241*, 155–176. https://doi.org/10.1023/A:1016125726789

Six, J., Elliott, E., Paustian, K., 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. *Soil Science Society of America Journal*, *63*, 1350–1358. https://doi.org/10.2136/sssaj1999.6351350x

Six, J., Elliott, E., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology & Biochemistry*, 32, 2099–2103. https://doi.org/10.1016/S0038-0717(00)00179-6

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C. Romanovskaya, A., Sperling, F., Tubiello, F., 2014. Agriculture, Forestry and Other Land Use (AFOLU). In: Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel J. Minx (Eds.), Climate

Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and USA. pp. 811–922. Disponible en: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5chapter11.pdf

Smith, P., 2016. Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, *22*, 1315–1324. https://doi.org/10.1111/gcb.13178

Sollins, P., Kramer, M. G., Swanston, C., Lajtha, K., Filley, T., Aufdenkampe, A. K., Bowden, R. D., 2009. Sequential density fractionation across soils of contrasting mineralogy: Evidence for both microbial- and mineral-controlled soil organic matter stabilization. *Biogeochemistry*, *96*, 209–231. https://doi.org/10.1007/s10533-009-9359-z

Solomon, D., Lehmann, J., Zech, W., 2000. Land use effects on soil organic matter properties of chromic Luvisols in semi-arid northern Tanzania: Carbon, nitrogen, lignin and carbohydrates. *Agriculture, Ecosystems & Environment*, 78, 203–213. https://doi.org/10.1016/S0167-8809(99)00126-7

Soussana, J.F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., Lal, R., 2019. Matching policy and science: Rationale for the ''4 per 1000 - soils for food security and climate'' initiative. *Soil and Tillage Research, 188*, 3–15. https://doi.org/10.1016/j.still.2017.12.002

Sparrow, L.A., Belbin, K.C., Doyle, R.B., 2006. Organic carbon in the silt plus clay fraction of Tasmanian soils. *Soil Use and Management*, *22*, 219–220. https://doi.org/10.1111/j.1475-2743.2006.00021.x

Stevenson, F. J.,1994. Humus chemistry: genesis, composition, reactions. John Wiley & Sons. https://doi.org/10.1021/ed072pA93.6

Stewart, C.E., Paustian, K., Conant, R.T., Plante, A.F., Six, J., 2007. Soil carbon saturation: concept, evidence and evaluation. *Biogeochemistry, 86*, 19–31. https://doi.org/10.1007/s10533-007-9140-0

Taguas, E.V., Vanderlinden, K., Pedrera-Parrilla, A., Giraldez, J.V., Gómez, J.A., 2017. Spatial and temporal variability of spontaneous grass cover and its influence on sediment losses in an extensive olive orchard catchment. *Catena*, *157*, 58-66. https://doi.org/10.1016/j.catena.2017.05.017

Taguas, E.V., Gomez, J.A., 2015. Vulnerability of olive orchards under the current CAP (Common Agricultural Policy) regulations on soil erosion: a study case in Southern Spain. *Land Use Policy, 42*, 683–694. https://doi.org/10.1016/j.landusepol.2014.09.001.

Taguas, E.V., Pena, A., Ayuso, J.A., Perez, R., Yuan, Y., Giraldez, J.V., 2010. Rainfall variability and hydrological and erosive response of an olive tree microcatchment under no-tillage with a spontaneous grass cover in Spain. Earth Surf. *Processes Landforms,* 35 (7), 750–760. https://doi.org/10.1002/esp.1893.

Telak, L.J., Pereira, P., Ferreira, C.S.S., Filipovic, V., Filipovic, L., Bogunovic, I., 2020. Short-Term Impact of Tillage on Soil and the Hydrological Response within a Fig (*Ficus Carica*) Orchard in Croatia. *Water*, *12*, 3295. https://doi.org/10.3390/w12113295

Tisdall, J. M., Oades, J. M., 1982. Organic matter and water-stable aggregates in soils. *Journal of soil science*, *33*(2), 141-163. https://doi.org/10.1111/j.1365-2389.1982.tb01755.x

Totsche, K. U., Amelung, W., Gerzabek, M. H., Guggenberger, G., Klumpp, E., Knief, C., Ray, N., 2018. Microaggregates in soils. *Journal of Plant Nutrition and Soil Science*, *181*(1), 104-136. https://doi.org/10.1002/jpln.201600451

Totsche, K.U., Rennert, T., Gerzabek, M.H., Kögel-Knabner, I., Smalla, K., Spiteller, M., Vogel, H.J., 2010. Biogeochemical interfaces in soil: The interdisciplinary challenge for soil science. *Journal of Plant Nutrition and Soil Science*, *173*(1), 88-99. https://doi.org/10.1002/jpln.200900105

Tubiello, F.N., Salvatore, M., Condor Golec, R., Rossi, S., Ferrara, A., Biancalani, R. Federici, S., Jacobs, H., Flammini, A., Olivier, J., House, J.I., Srivastava, N., Smith, P., 2015. The contribution of agriculture, forestry and other land use activities to global warming, 1990–2012. *Global Change Biology*, *21*:2655–2660. https://doi.org/10.1111/gcb.12865

Vanwalleghem, T., Laguna, A., Giraldez, J.V., Jimenez-Hornero, F.J., 2011. Applying a simple methodology to assess historical soil erosion in olive orchards. *Geomorphology 114*, 294–302. https://doi.org/10.1016/j.geomorph.2009.07.010.

Vasques, G.M., Grunwald, S., Comerford, N.B., Sickman, J.O., 2010. Regional modelling of soil carbon at multiple depths within a subtropical watershed. *Geoderma*, *156* (3–4), 326–336. https://doi.org/10.1016/j.geoderma.2010.03.002

Veerman, C., Bastioli, C., Biro, B., Bouma, J., Cienciala, E., Emmett, B., Frison, E.A., Grand, A., Filchev, L., Kriaučiūnienė, Z., Pinto Correia, T., Pogrzeba, M., Soussana, J-F., Vela, C., Wittkowski, R., 2020. Caring for soil is caring for life - Ensure 75% of soils are healthy by 2030 for food, people, nature and climate. Independent expert report, European Commission. *Publications Office of the European Union*. Luxembourg.

Vicente-Vicente, J.L., Gómez-Muñoz, B., Hinojosa-Centeno, M.B., Smith, P., Garcia-Ruiz, R., 2017.Carbon saturation and assessment of soil organic carbon fractions in Mediterranean rainfed olive orchards under plant cover management. *Agriculture, Ecosystems & Environment*, *245*, 135-146. https://doi.org/10.1016/j.agee.2017.05.020

Viscarra-Rossel, R.A., Webster, R., Bui, E.N., Baldock, J.A., 2014. Baseline map of organic carbon in Australian soil to support national carbon accounting and monitoring under climate change. *Global Change Biology*, *20* (9), 2953–2970. https://doi.org/10.1111/gcb.12569

Wang, X., Cammeraat, E., Cerli, C., Kalbitz, K., 2014. Soil aggregation and the stabilization of organic carbon as affected by erosion and deposition. *Soil Biology and Biochemistry*, *72*, 55-65. https://doi.org/https://doi.org/10.1016/j.soilbio.2014.01.018

Wang, Z.P., Han, X.G., Li, L.H., 2008. Effects of grassland conversion to croplands on soil organic carbon in the temperate Inner Mongolia. *Journal of Environment Management 86*, 529-534. https://doi.org/10.1016/j.jenvman.2006.12.004

Warkentin, B.P., 2008. Soil structure: A history from tilth to habitat. *Advances in Agronomy*, *97*, 239-272.

https://doi.org/https://doi.org/10.1016/S0065-2113(07)00006-5.

Wei, S., Zhang, X., McLaughlin, N. B., Chen, X., Jia, S., Liang, A., 2017. Impact of soil water erosion processes on catchment export of soil aggregates and associated SOC. *Geoderma*, *294*, 63-69. https://doi.org/10.1016/j.geoderma.2017.01.021

Wei, X., Shao, M., Gale, W., Li, L., 2014. Global pattern of soil carbon losses due to the conversion of forests to agricultural land. *Scientific Reports*, 4 (4062). https://doi.org/10.1038/srep04062.

Wiesmeier, M., Barthold, F., Spörlein, P., Geuß, U., Hangen, E., Reischl, A., Kögel-Knabner, I., 2014. Estimation of total organic carbon storage and its driving factors in soils of Bavaria (southeast Germany). *Geoderma Regional*, *1*, 67-78. https://doi.org/10.1016/j.geodrs.2014.09.001

Wiesmeier, M., Mayer, S., Paul, C., Helming, K., Don, A., Franko, U., Steffens, M., Kögel-Knabner, I., 2020. CO_2 certificates for carbon sequestration in soils: methods, management practices and limitations. *BonaRes Series*. https://doi.org/10.20387/bonares-ne0g-ce98

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., Wollschläger, U., 2019. Soil organic carbon storage as a key function of soils-a review of drivers and indicators at various scales. *Geoderma*, *333*, 149-162. https://doi.org/10.1016/j.geoderma.2018.07.026

Xiao, H., Li, Z., Chang, X., Huang, B., Nie, X., Liu, C., Jiang, J., 2018. The mineralization and sequestration of organic carbon in relation to agricultural soil erosion. *Geoderma*, *329*, 73-81. https://doi.org/10.1016/j.geoderma.2018.05.018

Xiong, X., Grunwald, S., Myers, D. B., Kim, J., Harris, W. G., Comerford, N. B., 2014. Holistic environmental soil-landscape modeling of soil organic carbon. *Environmental Modelling & Software*, *57*, 202-215. https://doi.org/10.1016/j.envsoft.2014.03.004

Xue, J.F., Pu, C., Zhao, X., Wei, Y.H., Zhai, Y.L., Zhang, X.Q., Zhang, H. L., 2018. Changes in soil organic carbon fractions in response to different tillage practices under a wheat-maize double cropping system. *Land Degradation & Development*, *29*(6), 1555-1564. https://doi.org/10.1002/ldr.2950

Zhang, Y., Li, X., Gregorich, E.G., McLaughlin, N.B., Zhang, X., Guo, Y., Sun, B., 2017. No-tillage with continuous maize cropping enhances soil aggregation and organic carbon storage in Northeast China. *Geoderma*, *330*, 204-211. https://doi.org/10.1016/j.geoderma.2018.05.037

Zhao, L., Sun, Y., Zhang, X., Yang, X., & Drury, C. F. (2006). Soil organic carbon in clay and silt sized particles in Chinese mollisols: relationship to the predicted capacity. *Geoderma*, *132*(3-4), 315-323. https://doi.org/10.1016/j.geoderma.2005.04.026

Zinn, Y.L., Lal, R., Bigham, J.M., Resck, D.V.S., 2007. Edaphic controls on soil organic carbon retention in the Brazilian cerrado: texture and mineralogy. *Soil Science Society of America Journal*, 71 (4), 1204–1214. https://doi.org/10.2136/sssaj2006.0014

Zomer, R.J., Bossio, D.A., Sommer, R., Verchot, L.V., 2017. Global sequestration potential of increased organic carbon in cropland soils. *Scientific Reports, 7(1), 1-8.* https://doi.org/10.1038/s41598-017-15794-8

Hipótesis y Objetivos

2. HIPÓTESIS Y OBJETIVOS.

Ante los nuevos planteamientos ambientales en el marco de la agricultura en la Unión Europea se hacen necesarios estudios en profundidad del recurso suelo sobre el que se sustenta la agricultura.

El suelo es un recurso natural finito y no renovable que provee de diferentes servicios ecosistémicos y ambientales, incluyendo aquellos relacionados con los ciclos biogeoquímicos como el del carbono, nitrógeno, fósforo, etc. Además, el suelo constituye la base de la producción de alimentos y materiales de la que la humanidad depende (Montanarella, 2015). El suelo tiene una influencia considerable en el medio ambiente en el que se sitúa y tiene repercusiones en las actividades sociales y económicas de la población que ocupa ese territorio, población que ejerce una presión sobre ese suelo ocasionando su degradación cuando la presión sobrepasa la capacidad de acogida. (Gardi *et al*., 2014).

Es por todo ello que los objetivos planteados son:

1) Analizar las dinámicas de almacenamiento de carbono y nitrógeno a largo plazo en olivar, mostrando la evolución de su distribución tanto en superficie como en profundidad a través del estudio de los horizontes del suelo.
2) Valorar cómo diferentes prácticas de manejo, laboreo convencional (CT), no laboreo con suelo desnudo mediante la aplicación de herbicidas (NT+H) y no laboreo con cubierta espontanea (NT-CC), influyen en el secuestro y almacenamiento de SOC en suelos de olivar.

3) Evaluar el estado de cumplimiento de la Iniciativa 4 por mil en suelos de olivar bajo diferentes prácticas de manejo.
4) Estudiar la estabilidad estructural de los suelos de olivar mediante los agregados del suelo y la distribución del SOC como reservorio en las diferentes fracciones.
5) Analizar el impacto de la inclusión de la cubierta vegetal y el cambio de manejo en suelos de olivar en diferentes posiciones topográficas.
6) Estimar las tasas de erosión en el área de estudio y su influencia a largo plazo en la productividad del suelo y las propiedades físicas.

Material y Métodos

3. MATERIAL Y MÉTODOS

3.1 Área de estudio.

La zona de estudio se sitúa dentro del municipio andaluz de Torredelcampo (Jaén). Esta área se sitúa geomorfológicamente entre dos unidades territoriales superiores denominadas Campiña de Jaén y Sierra sur de Jaén (Guzmán-Álvarez, 2004), siendo una zona de transición entre ambas. El área de estudio se caracteriza por unos relieves donde la acción erosiva sobre materiales sedimentarios ha dejado formas suaves y de baja altitud, con cumbres redondeadas y laderas de pendientes moderadas (Figura 27), aunque alejados de la uniformidad de las campiñas (Ramírez, 2013) y nítidamente diferenciados de los paisajes olivareros contiguos de Sierra Mágina.

Figura 27. Vista general del área de estudio. Imagen propia.

Las parcelas de estudio (37°46′26.0″N, 3°54′41.5″W) (Figura 28) se encuentran en la zona noreste del término municipal de Torredelcampo, a 540 metros sobre nivel del mar. En cuanto a las condiciones climáticas, son típicas del clima Mediterráneo, caracterizadas por un fuerte contraste térmico, con grandes diferencias entre los meses fríos y cálidos. Las temperaturas medias anuales se sitúan en 17,1º C con máximos por encima de 45º C en los meses de verano y mínimas por debajo de 0º C en los meses de invierno. En cuanto a las precipitaciones medias anuales se situaron en 493,2 mm para el periodo (1983-2010), con una baja pluviometría en los meses de verano (junio a septiembre) y frecuentes sequías. Las parcelas de estudio presentan una orientación suroeste, con una pendiente media del 6%.

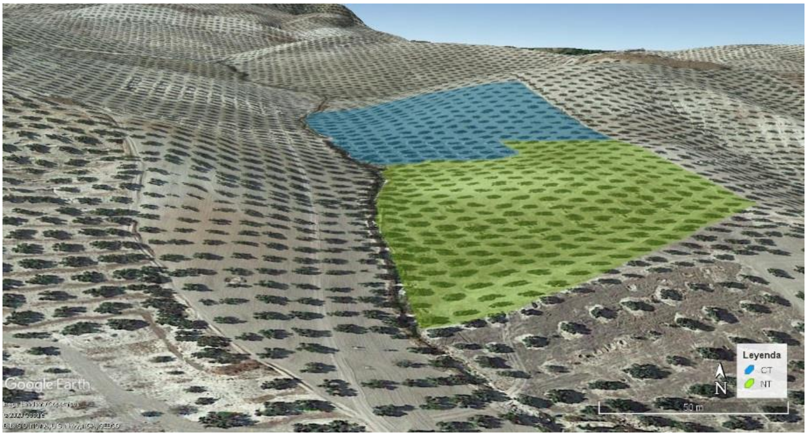


Figura 28. Parcelas de estudio. CT: laboreo convencional; NT: no laboreo con suelo desnudo por aplicación de herbicidas. Elaboración propia.

En cuanto a la clasificación de los suelos, pueden definirse como Cambisoles calcáreos (FAO, 2015) que se caracterizan por la meteorización del material parental de origen sedimentario (calizas y margas), con un alto contenido en arcillas y carbonato cálcico que se distribuyen de forma homogénea dentro del perfil.

El cultivo de olivar (*Olea europaea*, variedad Picual) que se instala en las parcelas de estudio se puede definir como olivar de tipo extensivo, con una densidad de 90 árboles por hectárea y amplios marcos de plantación (12 m x 12 m) con dos o tres patas por árbol.

La zona de estudio cubre un área de 10 ha aproximadamente, dentro de ella se pueden diferenciar dos prácticas de manejo que conviven desde el año 2004, laboreo convencional (CT) (Figura 29) y no laboreo con suelo desnudo y aplicación de herbicidas (NT+H).

Figura 29. Parcela bajo manejo de laboreo convencional. Imagen propia.

Ambas parcelas han recibido la misma dosis y tipo de fertilizantes químicos (100 kg ha^{-1} de urea, riqueza de N 46%) que se aplican después de la cosecha de la aceituna (enero-febrero) en años alternos. Las podas de los olivos se realizan cada dos años y los restos (6 Mg ha^{-1}) son triturados entre las calles de los olivos. Además, se aplican fungicidas (oxicloruro de cobre 34,5%) para el control de enfermedades como el repilo (*Spilocaea oleagina*) o la tuberculosis (*Pseudomonas savastanoi*). Para el control de la flora arvense en ambos tratamientos se aplican herbicidas de preemergencia de amplio espectro (1 L 36% de glifosato ha^{-1}) en los meses de otoño, en años lluviosos pueden realizar otra aplicación en primavera, con el que se consigue mantener la parcela libre de vegetación durante todo el año.

Figura 30. Parcela bajo manejo de no laboreo más herbicidas. Imagen propia.

La parcela bajo NT+H (Figura 30) se ha manejado durante el periodo de estudio sin labores mecánicas aplicadas al suelo, mientras que la parcela manejada bajo CT se ha labrado en primavera con un cultivador seguido de una rastra de púas y en verano con un arado de discos (25 cm) para disminuir el tamaño de los terrones.

Desde 2017 se ha incluido una tercera práctica de manejo (Figura 31) consistente en el mantenimiento de una cubierta espontánea (NT-CC).

Bajo este manejo se mantiene la aplicación de restos de poda del olivar, pero la aplicación de herbicidas y el laboreo se han suprimido. El control de la vegetación que forma la cubierta se realizó mediante pases de desbrozadora en los meses de primavera, para evitar competencias por agua durante los meses con mayor déficit de lluvias.

Figura 31. Parcela con cubierta espontánea. Imagen propia.

3.2. Toma de muestras y preparación.

La recogida de muestras de suelo inicial se realizó en el año 2004 en la parcela bajo CT, previamente al cambio de manejo en parte de la finca hacia NT+H. En el año 2017 se volvió a muestrear el área de estudio después de la inclusión del manejo NT-CC. Por último, en 2019 se volvió a muestrear la zona tomando muestras de los tres manejos que se implantaron (CT, NT+H y NT-CC) a lo largo del periodo de estudio. Las muestras de suelo se tomaron horizonte por horizonte en perfiles completos a una profundidad aproximada de 120 cm (Figura 32). Las parcelas fueron divididas en subparcelas donde se abrieron un total de 5 perfiles en cada una de ellas. Además, en las diferentes posiciones topográficas, parte alta, media y baja de la ladera, 3 perfiles fueron abiertos. Estos perfiles fueron descritos y catalogados y las muestras recogidas se transportaron en el mismo día en bolsas de plástico al laboratorio para su posterior análisis.

Figura 32. Perfiles abiertos en el área de estudio. Imagen propia.

Una vez en el laboratorio, las muestras se secaron al aire a temperatura ambiente y posteriormente fueron tamizadas a 2 mm y 8 mm dependiendo de los análisis posteriores.

3.3 Métodos analíticos.

3.3.1 Densidad aparente.

La determinación se realizó a partir del método de Blake y Hartge (1986) donde muestras no alteradas de suelo son tomadas en campo en cilindros metálicos de 3 cm de diámetro, 10 cm de altura y 70,65 cm^3 de volumen, que luego se secan en estufa a 105 ºC hasta peso constante. El cálculo de la densidad aparente se determina como el cociente entre el peso seco de la muestra de suelo y el volumen del cilindro.

3.3.2 Contenido en gravas.

El contenido en gravas del suelo se determinó a partir de tamizar las muestras con un tamiz de malla de luz de 2 mm. La muestra que pasó el tamiz se pesó y la que quedó sobre el tamiz también para luego expresarse como el porcentaje de gravas.

3.3.3 Textura.

El análisis de la granulometría del suelo (Figura 33) se realizó mediante el método del densímetro de Bouyucos (USDA, 2004). Posteriormente a un tratamiento con peróxido de hidrógeno al 6%, las muestras se llevan a sequedad total y a continuación se procede a su dispersión, para lo cual se introducen en un bote de agitación añadiendo 25 mL de una disolución de hexametafosfato sódico al 10% y unos 300 mL de agua destilada. El contenido del bote de agitación se pasa a una probeta de 1000 mL arrastrando con el frasco lavador todas las partículas. Una vez enrasada hasta la señal de 1000 mL, se agita para homogeneizar la suspensión y se introduce el densímetro, anotando la lectura a los 40 segundos y a las dos horas. Estas medidas informan sobre la distribución de partículas minerales de la fracción fina del suelo (< 2000 µm) según diferentes tamaños, obteniendo el conenido textural del suelo donde se diferencia entre arenas (2000-50 µm), limos (50-2 µm) y arcillas (< 2 µm).

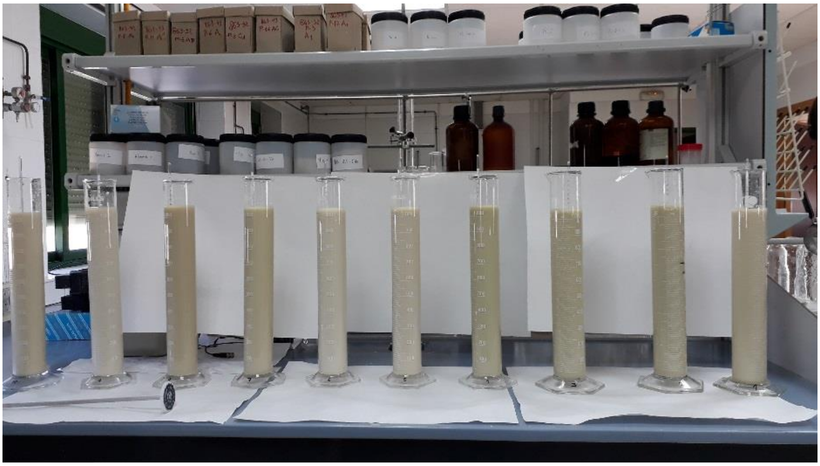


Figura 33. Determinación textural del suelo del área de estudio. Imagen propia.

3.3.4 pH.

Para determinar el pH del suelo se utilizó el método de Guitián y Carballas (1976). Las muestras de suelo en suspensión en agua (proporción 1:2,5) se agitan 10 minutos y se dejan reposar 30 minutos, a continuación, se les realiza la medición con el pH-metro provisto con electrodo de vidrio (Crison-2002).

3.3.5 Estabilidad estructural.

Para el análisis de la estabilidad estructural y de los agregados del suelo se utilizó el procedimiento de tamizado en húmedo de Elliot (1986) (Álvaro-Fuentes *et al.*, 2019). En este procedimiento, se realiza en primer lugar un tamizado, con tamiz de 8 mm, del que se extrae 100 g de muestra de suelo totalmente seca. Esta muestra es tamizada en húmedo para obtener cuatro fracciones de agregados usando tamices de 2000, 250 y 53 µm de diámetro. Las muestras de suelo se colocan en la parte superior de un tamiz de 2000 µm y se sumergen durante 5 min en agua a temperatura ambiente. Después de la humectación de la muestra el tamiz se mueve manualmente 50 veces arriba y abajo durante 2 minutos aproximadamente para lograr la separación de las diferentes fracciones de agregados: (i) grandes macroagregados (>2000 µm), (ii) pequeños macroagregados (250-2000 µm), (iii) microagregados (53-250µm) y (iv) limo y arcilla (<53µm) (Figura 34).

Figura 34. Fraccionamiento del suelo del área de estudio.

3.3.6 Capacidad de retención de agua.

De acuerdo con el método de Richards (1947), en primer lugar, las muestras de suelo se disponen sobre placas y son llevadas, mediante incorporación de agua, a estado de saturación. Posteriormente, se someten a presión de 33 kPa y 1500 kPa en ollas de presión tipo Richards para extraer el exceso de agua. Por último, las muestras de suelo se secan en estufa a 105 ºC para determinar el contenido de humedad de cada una de ellas. La retención de agua en las muestras a 33 kPa se considera la humedad del suelo a capacidad de campo, mientras que la retención a 1500 kPa equivale al contenido de agua del suelo en el punto de marchitez permanente. De la diferencia entre ambas determinaciones se obtiene el agua disponible del suelo para las plantas.

3.3.7 Tasa de infiltración.

La capacidad de infiltración del suelo del área de estudio se determinó en campo mediante el método del anillo simple (Álvaro-Fuentes *et al*., 2019). Mediante este procedimiento se insertan tubos de PVC (diámetro = 15 cm y altura = 12 cm) en cada tratamiento, a una profundidad aproximada de 1-2 cm para evitar la pérdida de agua y producir la mínima perturbación del medio poroso. Se vierte un volumen de agua conocido (150 mL) dentro del anillo al comienzo de la medición y se registra el tiempo necesario para que el agua se infiltre. Una vez que el agua se infiltra completamente, se añade nuevamente agua y se registra el tiempo necesario para su completa infiltración. Este procedimiento se repite hasta que el tiempo de infiltración se mantiene estable (5-7 veces dependiendo del tratamiento).

Figura 35. Determinación de la tasa de infiltración. Imagen propia.

3.3.8 Carbonatos.

La determinación del contenido en carbonatos de las muestras de suelo se analizó mediante el método del calcímetro de Bernard (Muller y Gastner, 1971). Según este método el contenido en carbonatos se determina mediante la reacción del suelo en contacto con ácido clorhídrico al 50%. El CO_2 desprendido en la reacción desplaza una solución salina saturada contenida en una bureta graduada.

3.3.9 Carbono orgánico del suelo (SOC).

El método empleado se basa en el método de Walkley y Black (Nelson y Sommers, 1982). De acuerdo con este método, la oxidación de la materia orgánica se realiza mezclando la muestra de suelo en una solución acuosa de 20 mL de dicromato potásico ($K_2Cr_2O_7$) en presencia de 15 mL de ácido sulfúrico, para luego agitar y dejar reposar durante 30 minutos la mezcla. Posteriormente se le añade agua a la mezcla y luego es filtrada. Finalmente se realiza la medida colorimétrica del Cr (III) procedente de la reducción del dicromato. La absorbancia se realizó en un espectrofotómetro a 600 nm, longitud de onda a la que absorbe el Cr (III), tras realización de la recta de calibrado mediante una disolución de glucosa (25 g/L).

El contenido de materia orgánica de las muestras de suelo se calcula una vez determinado el contenido de carbono del suelo multiplicando el porcentaje de carbono por 1,8.

3.3.10 Nitrógeno total (TN).

El nitrógeno total fue determinado mediante el método de Kjeldahl (Bremer, 1996). Con este método la muestra de suelo se somete a una digestión junto con selenio, sulfato de cobre y sulfato de potasio además de ácido sulfúrico (H_2SO_4). Seguidamente se destila la mezcla por arrastre de vapor, añadiéndose NaOH (35 %) de este modo se desplaza el amoniaco (NH_3) que se recoge en H_2SO_4. Finalmente se valora el H_2SO_4 que no ha reaccionado con el NH_3 arrastrado con hidróxido de sodio (NaOH 0.1 N) de concentración conocida. La relación C:N fue calculada dividiendo la concentración SOC entre la concentración de TN.

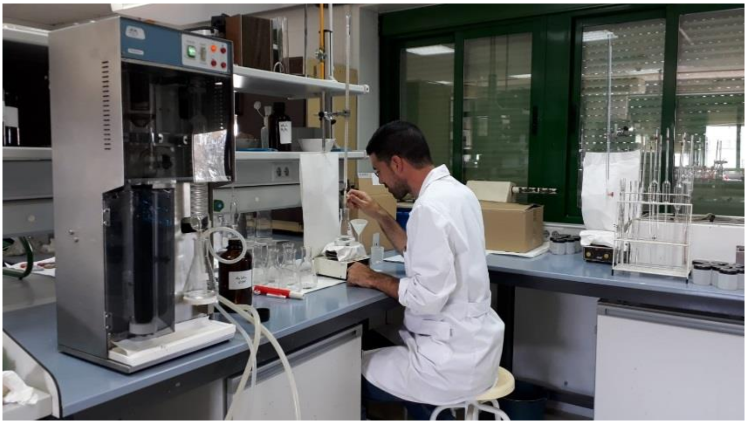


Figura 36. Determinación de nitrógeno. Imagen propia.

3.4 Manejo de datos.

3.4.1 *Stock* de carbono orgánico (SOC-S).

A partir del *stock* de carbono se conoce el contenido en carbono orgánico de un área determinada. Se expresa en Mg ha^{-1} y se calcula a partir de la siguiente fórmula (IPCC, 2003):

$$SOC\ S = SOC \times BD \times d \times (1 - \delta 2\, mm\,\%) \times 10^{-1}$$

donde SOC es el contenido de carbono orgánico del suelo (g kg^{-1}), BD es la densidad aparente (Mg m^{-3}), d es el espesor del horizonte (cm) y δ2 mm es el porcentaje de la fracción de gravas (>2 mm).

3.4.2 *Stock* de nitrógeno total (TN-S).

De igual modo que el SOC-S se calculó el *stock* de nitrógeno (TN-S) en las parcelas de estudio expresado en Mg ha^{-1}:

$$TN\ S = TN \times BD \times d \times (1 - \delta 2\, mm\,\%) \times 10^{-1}$$

donde TN es el contenido de nitrógeno del suelo (g kg^{-1}), BD es la densidad aparente (Mg m^{-3}), d es el espesor del horizonte (cm) y δ2 mm es el porcentaje de la fracción de gravas (>2 mm).

3.4.3 Ratio de almacenamiento de C.

Para la evaluación del almacenamiento de C y la iniciativa 4x1000 se aplicó la fórmula de la ratio de almacenamiento de carbono (CSR) (Francaviglia *et al*., 2019) expresada en Mg C ha^{-1} $año^{-1}$.

$$CSR\ (por\ 1000) = [(SOCf - SOCi)\ /nº\ de\ años]\ /\ SOCi\ x\ 1000$$

donde SOCf y SOCi son la concentración final e inicial de SOC-S (Mg ha^{-1}) entre el número de años del estudio.

3.4.4 Diámetro medio ponderado de los agregados (MWD).

El MWD se calculó como indicador de la estabilidad del suelo y para su posterior categorización de acuerdo con Le Bissonnais (1996). La determinación se realizó a partir de la fórmula desarrollada por Kemper y Rosenau (1986):

$$MWD = \sum_{i=1}^{4} x_i w_i$$

donde X_i es el diámetro medio de cada tipo de fracción (macroagregados grandes >2000 µm; macroagregados pequeños 250-2000 µm; microagregados 53-250 µm; limo y arcilla <53 µm), y W_i la proporción de agregados de la muestra en la fracción del tamaño correspondiente.

3.4.5 Estimación de las pérdidas de suelo.

El modelo *Revised Universal Soil Loss Equation* (RUSLE) desarrollado por Renard *et al*. (1997) para la estimación de pérdidas de suelo es una metodología ampliamente reconocida y su aplicación está muy extendida dentro de la comunidad científica. La ecuación básica del modelo RUSLE para la estimación de las pérdidas medias de suelo como consecuencia de la erosión hídrica laminar y en regueros, es la siguiente:

$$A = R * K * C * LS * P$$

donde A: pérdida anual de suelo (Mg $ha^{-1}año^{-1}$), R = Erosividad de la lluvia (MJ mm ha^{-1} h^{-1} $año^{-1}$), K = Erodabilidad del suelo (Mg ha h ha^{-1} MJ^{-1} mm^{-1}), LS = longitud de la pendiente en metros y el gradiente, C = Factor cobertura y manejo del suelo, P = Prácticas de conservación del suelo. En el apartado 4.4 se describe en mayor detalle el cálculo de los diferentes factores que forman la ecuación principal.

3.4.6 Índice de productividad del suelo.

La premisa básica del índice de productividad es que, para mantener la sostenibilidad de los recursos del suelo, la productividad del suelo (expresada por algunas propiedades medibles del suelo) no debe ser inferior a un cierto valor crítico en un tiempo determinado. Para ello se aplicó la siguiente fórmula desarrollada por Pierce *et al*. (1983) y modificada por Xingwu *et al*. (2015)

$$PI = \sum_{i=1}^{3} A_i \, x \, C_i \, x \, D_i \, x \, O_i \, x \, WF_i$$

donde PI es el índice de productividad (0-1), Ai es la suficiencia de AWC, Ci es la suficiencia de la densidad aparente, Di es la suficiencia del pH, Oi es la suficiencia de la materia orgánica en la capa i del suelo y WFi es un factor de ponderación que representa una distribución idealizada de las raíces de las plantas, lo que refleja que las diferentes capas del suelo tienen diferentes impactos en la productividad de este.

3.4.5 Análisis estadístico.

Para la realización del análisis estadístico se usó el programa SPSS 13.0 para Windows. Las diferencias entre los diferentes manejos, las posiciones topográficas, la profundidad y las variables estudiadas fueron evaluadas mediante el análisis de la varianza (ANOVA). Considerando estadísticamente significativas las diferencias de $p < 0,05$.

3.5 Referencias.

Álvaro-Fuentes, J., Lóczy, D., Thiele-Bruhn, S., Zornoza, R., 2019. Handbook of plant and soil analysis for agricultural systems (Version 1.0). Zenodo. http://doi.org/10.5281/zenodo.2553445.

Bremner, J.M., 1996. Total nitrogen. SSSA Book Series No 5. In: Sparks, D.L. (Ed.), Methods of Soil Analysis. Part 3. Chemical Methods. Soil Science Society of America, Madison, WI, pp. 1085–1086

Elliott, E.T., 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Science Society of America Journal, 50 (3), 627–633. https://doi:10.2136/sssaj1986.03615995005000030017x

Francaviglia, R., Di Bene, C., Farina, R., Salvati, L., Vicente-Vicente, J.L., 2019. Assessing "4 per 1000" soil organic carbon storage rates under Mediterranean climate: a comprehensive data analysis. Mitigation and Adaptation Strategies for Global Change, 24, 795–818. https://doi.org/10.1007/s11027-018-9832-x

Guitián, F., Carballas, T., 1976. Técnicas de Análisis de Suelos. Picro Sacro, Santiago de Compostela, España.

Guzmán-Álvarez, J.R., 2004. Geografía de los paisajes del olivar andaluz.

IPCC, 2003. *Good Practice Guidance for Land Use, Land Use Change and Forestry* [Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F. (Eds.)]. IPCC/OECD/IEA/IGES, Hayama, Japan.

FAO, I. Working Group WRB, 2015. World reference base for soil resources 2014, update 2015. *International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports*, (106).

Kemper, W.D., Rosenau, R.C., 1986. Aggregate stability and size distribution. In: Klute, A. (Ed.) Methods of soil analysis. Part 1.2 inded. Agron. Monogr. 9. ASA, Madison, WI, pp. 425‑442

Le Bissonnais, Y., 1996. Aggregate stability and assessment of crustability and erodibility:1. Theory and methodology. European Journal of Soil Science. 47, 425‑437. https://doi.org/10.1111/ejss.2_12311.

Müller, G., Gastner, M., 1971. The 'Karbonat-Bombe', a simple device for the determination of carbonate content in sediment, soils, and other materials. *Neues Jahrbuch für Mineralogie-Monatshefte*, 10, 466-469.

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon and organic matter. In: Page, A.L., Miller, R.H., Keeney, D. (Eds.), Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. Agronomy Monograph. 9. ASA and SSSA, Madison, WI, pp. 539–579.

Pierce, F. J., Larson, W. E., Dowdy, R. H., Graham, W. A. P., 1983. Productivity of soils: assessing long-term changes due to erosion. *Journal of Soil and Water Conservation*, 38(1), 39-44.

Ramírez, J. N., 2013. Las campiñas del Guadalquivir: claves para una interpretación geográfica. *Revista de Estudios Regionales*, (96), 99-134.

Richards, L.A., 1941. Pressure-Menbrana apparatus construction and use. Agricultural Engineers, 28, 451–454.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C., 1997. Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). US Department of Agriculture Agricultural Handbook No. 703. USDA Washington DC.

USDA, 2004. Soil survey laboratory methods manual. Soil survey investigation report no. 42. USDA-NCRS, Lincoln, NE, Version 4.0.

Xingwu, D., Li, R., Guangli, Z., Jinming, H., Haiyan, F., 2015. Soil productivity in the Yunnan province: Spatial distribution and sustainable utilization. *Soil and Tillage Research*, 147, 10-19. https://doi.org/10.1016/j.still.2014.11.005

Resultados y discusión

Long-term evaluation of the initiative 4‰ under different soil managements in Mediterranean olive groves

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Long-term evaluation of the initiative 4‰ under different soil managements in Mediterranean olive groves

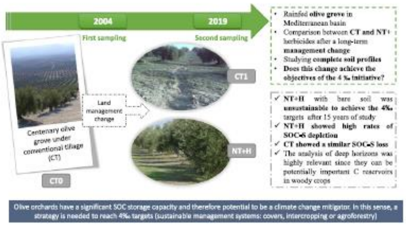
Manuel González-Rosado, Luis Parras-Alcántara, Jesús Aguilera-Huertas, Beatriz Lozano-García *

Department of Agricultural Chemistry, Soil Science and Microbiology, Faculty of Science, Agrifood Campus of International Excellence - ceiA3, University of Córdoba, 14071 Córdoba, Spain

HIGHLIGHTS

- We determined the effects of long term management change in the soil profile.
- Olive groves under conventional tillage obtained important SOC and TN stock losses.
- No till + herbicide showed greater loss rates of SOC and TN stocks than CT.
- SOC stock in deep horizons was important because they can be important C reservoirs.
- CT nor No till + herbicide with bare soil did not achieve the 4‰ targets.

GRAPHICAL ABSTRACT



4.1.1. Introduction.

The 4‰ initiative agreed at the 21 Conference of the parties to the United Nations Framework Convention on Climate Change (COP21) in Paris proposes that the world's soils increase the content of soil organic carbon (SOC) at a rate of 0.4% per year to mitigate the emission of greenhouse gases (GHGs) (UNFCC, 2015). Therefore, the current agricultural model has the challenge of sustainable use of resources to mitigate the effects of climate change and the productivity of farms in favour of food security (Lal, 2016).

To this aim, it is essential to practice management systems that promote carbon sequestration and increase the stock of carbon in soils. Olive groves, as an agro-ecosystem of significant territorial, economic, environmental and cultural importance, are essential when confronting these processes of environmental and productive compatibility.

Olive groves have an extent of 4.6 million ha in Europe (EUROSTAT, 2018), with Spain being the main country of olive oil production. Olive groves in Spain show a great agronomic and productive diversity and are one of the most important crops in extent, covering 2.697.445 ha in 2018, according to data from the Ministry of Agriculture, Fisheries and Food (MAPA, 2018a). Furthermore, in recent years in Spain, the percentage of new plantations has increased by 4.2% between 2012 and 2018 (MAPA, 2018b). In this period, Andalusia is where one of the greatest increases in the area of new plantations has been registered, with a 4.6% increase, reaching 1.630.473 ha, which places this region with 60.4% of the total olive grove area in Spain (MAPA, 2018b). Among the Andalusian provinces, Jaén and Córdoba have 36.4 and 22.6% of the total area of Andalusian olive groves respectively, which represent the highest levels of an area dedicated to olive groves, well above the rest of the provinces of the region.

In the evolution of the management of Andalusian agroecosystems where olive groves are inserted, both the expansion and the intensification in olive groves have increased production (Andreu-Lara *et al*., 2013). At the same time, there has been an environmental degradation increment based on the loss of biodiversity, with the elimination of vegetation cover with the consequent increase in erosion rates (Sastre *et al*., 2018) and the contamination of water and soil as a result of the use of fertilisers and phytosanitary products (Pastor, 2004; Infante, 2011).

Managed agricultural lands that have been undergone degradation processes have a high potential to become soils that sequester soil organic carbon (SOC) (Minasny *et al*., 2017; Abbas *et al*., 2020). In this recarbonisation process, it is fundamental to implement soil management practices that promote the increase of the SOC content (Vicente-Vicente *et al*., 2016) and its permanence in the SOC stock (Lal, 2018). In this sense, these agricultural lands face an important challenge the transition from carbon emitting areas to carbon sequestration areas.

Mediterranean olive groves are usually cultivated in semiarid areas characterized by low organic matter (OM) content (Vicente-Vicente *et al*., 2016). Conventional tillage (CT) is a common practice in rainfed olive orchards. Farmers use frequent and intense tillage to fight against the competition for water and nutrients between weeds and olive trees (Ramos *et al*., 2010). However, CT is reported as an important driver of both the low soil OM level and the loss of structure, which conduct to less water availability in the soil (González-Rosado *et al*., 2020a).

Increasing the SOC is a win-win strategy due to implying both better soil quality and a reduction in the GHGs level. A good option to sequester C in olive grove soils is by using recommended practices, such as the use of cover crops, the reduction of tillage and/or the addition of organic amendments (Vicente-Vicente *et al*., 2016).

In the last decades, many farmers afraid of the reduction in the yields have changed to no-tillage plus herbicides (NT1+H) as a more conservative agricultural practice while maintaining bare soil by the application of pre-emergence herbicides to avoid natural covers that compete for water and nutrients with olive trees. However, effective studies are required to evaluate the effects of land management change on SOC stocks and soil contribution as a C sink for policy decisions in Mediterranean olive groves.

Therefore, this study was conducted to compare the long-term effect of management change (from CT to NT1 + H) in olive groves with the long-term effects of CT and to demonstrate if with this change the objectives of the 4‰ initiative could be achieved. To this end, we studied the temporal dynamics of SOC and TN distribution and changes along with the complete soil profiles in a Mediterranean area after 15 years under CT and NT practices in a rain-fed olive grove.

4.1.2. Material and methods.

4.1.2.1. Site description and climatic parameters.

The study area is located in Torredelcampo (Jaén), in the south-east Mediterranean region of Spain (37° 50′ 55″ N, 03° 51′ 55″ W) (Figure 1).

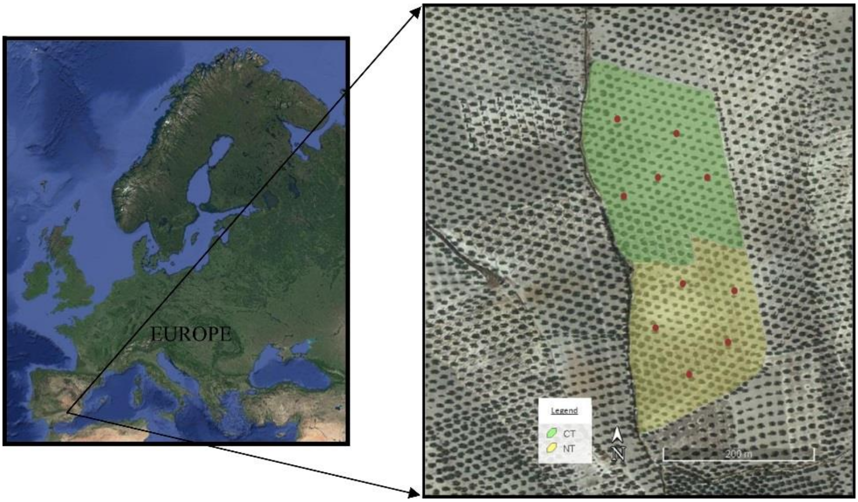


Figure 1. Location of the experimental farm at Torredelcampo, Jaén, Spain. Study areas are highlighted with different colours: Conventional tillage (CT1) in green, and no tillage+bare soil by using herbicides (NT1+H) in yellow. Red circles represent soil sampling points.

The elevation is 540 m.a.s.l. and the slope ranges from 1 to 10%. The representative soil in the experimental area is classified as Calcaric Cambisol (FAO, 2015). This type of soil is characterized by weathering of the parent material (limestone and marls) and the high content of clays and carbonates that are distributed homogeneously in the profiles (Table 1).

Tillage practice	Hor.	Depth (cm)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	BD (Mg m^{-3})	pH (H_2O)	OM (%)	C:N
CT0	Ap	0-27.3	12.8±1.7Aa	8.7±0.6 Aa	19.8±1.5Aa	71.5±0.9Aa	1.41±0.03Aa	7.72±0.10Aa	1.22±0.06Aa	7.0±0.8Aa
	Bw	27.3-56.0	13.6±1.5Aa	5.5±1.6 Ba	22.9±1.4Aa	71.6±0.6Aa	1.42±0.02Aa	8.02±0.11Aa	1.01±0.05Aa	5.7±0.5Ba
	BC	56.0-89.0	17.6±1.2 Ba	3.8±0.8Ca	24.8±1.7Aa	71.4±1.9Aa	1.43±0.03Aa	8.15±0.05Aa	0.76±0.04Ba	4.6±0.2 Ba
	C	89.0-115.7	12.6±0.5Aa	4.1±0.9Ca	21.9±1.6Aa	74.0±0.7Aa	1.44±0.02 Ab	8.07±0.10 Aa	0.71±0.02 Ba	4.9±0.4Ba
CT1	Ap	0-32.7	15.6±3.6Aa	9.2±5.2Aa	19.1±5.0Aa	71.6±2.8Aa	1.35±0.14 Aa	7.81±0.10Aa	0.88±0.29 Ab	6.1±0.8Aa
	Bw	32.7-65	15.8±5.1Aa	3.6±4.4Ca	21.0±2.0Aa	75.3±7.0Aa	1.35±0.07 Aa	8.11±0.10Aa	0.59±0.10Bb	5.1±0.8Aa
	BC	65-89.7	21.7±2.2 Ba	6.5±3.6Ba	20.6±4.8Ab	72.9±2.8Aa	1.37±0.09 Aa	8.17±0.05Aa	0.38±0.19Cb	6.3±0. 5Ab
	C	89.7-119.7	12.2±0.3Aa	9.7±0.5Ab	21.5±0.1Aa	68.7±2.2Ab	1.39±0.04 Ab	8.11±0.13 Aa	0.29±0.14 Cb	5.4±0.8Aa
NT1+H	A	0-21.7	15.0±2.5 Aa	9.8±2.1 Aa	26.7±5.9Ab	63.5±4.8Ab	1.37±0.07 Aa	7.82±0.07Aa	0.74±0.20Ab	10.2±1.2Ab
	Bw	21.7-60	17.6±2.1 Aa	12.9±5.6 Ab	25.9±4.9 Aa	61.2±6.2Ab	1.40±0.03 Aa	8.09±0.17 Aa	0.43±0.18Bb	9.5±2.2 Ab
	BC	60-84.7	21.5±1.2 Ba	12.3±9.6Ab	29.1±5.5 Aa	58.6±7.9Ab	1.42±0.04 Aa	8.05±0.09 Aa	0.27±0.09 Cb	6.4±1.6 Bb
	C	84.7-110	12.7±0.8 Aa	6.9±0.72Ba	24.8±3.4 Aa	68.2±7.6Ab	1.39±0.03 Aa	8.17±0.13 Aa	0.27±0.09 Cb	6.4±1.6 Bb

Table 2. Basic soil physical and chemical properties for Cambisol in olive grove. Data are means ± SD.
D (a.v.):CT0: conventional tillage 2004; CT1: conventional tillage 2019; NT1+H: no tillage; Hor: Horizon type; Depth: Horizon thickness; BD: Bulk density; OM: Organic matter; C:N:C:N ratio.
Numbers followed by different capital letters within the same column have significant differences ($P < 0.05$) between depths considering the same land use.
Numbers followed by different lower case letters within the same column have significant differences ($P < 0.05$) between the same soil horizon in different land use considering the same variable.

During the study period (2004–2019), the average annual air temperature of the experimental area was 16.6 °C, and the mean annual precipitation was 458.8 mm, with hot and dry summers and cold winters.

These climatic characteristics are typical of a semiarid Mediterranean climate. The average monthly evapotranspiration and mean monthly precipitation during the analysed period are shown in Figure 2 (Junta de Andalucía, 2020).

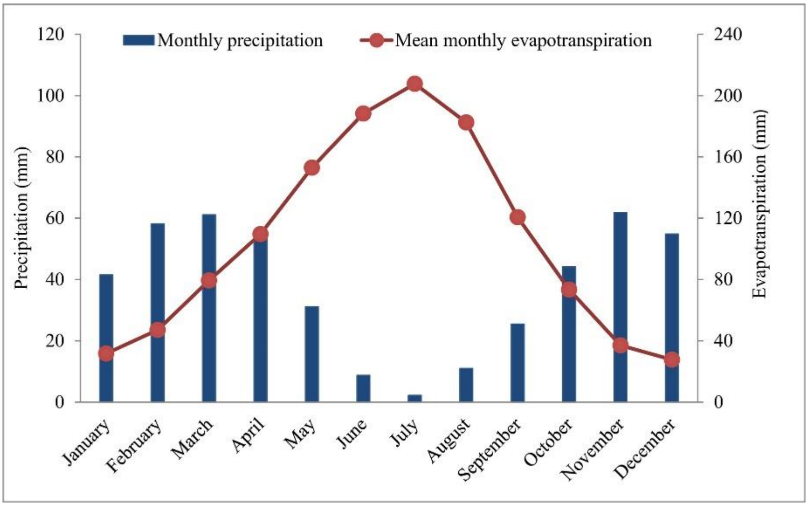


Figure 2. Mean monthly evapotranspiration and monthly precipitation during the research period at study area.

4.1.2.2. Experimental design.

This study began in 2004 analysing the main characteristics of soil under CT (CT0) in an olive grove by horizons, considering complete soil profiles. The field experiment was established in a rain-fed olive grove, ‘Picual’ variety with 2–3 trunks, planted in a pattern of 12 × 12 m, covering an area of approximately 10 ha. In 2004, the studied area was divided into two plots with different management: CT1 the first one, managed under conventional tillage (disc harrowed in summer [25 cm] to diminish the size of soil clods) such as it was from the last century in CT0, and NT1 + H with bare soil the second one. Both plots received the same rate and type of chemical fertilisers in the winter season (100 kg ha^{-1} urea, N richness 46%) in alternate years were applied after the olives had been harvested), with the same application of pruning residues (6 Mg ha^{-1} each 2 years) and fungicides (copper oxychloride 34.5% w.p.). In both treatments, vegetation was eliminated by applying pre-emergence herbicides (1.0 L 36% glyphosate ha^{-1}) in autumn to control weeds. The NT1 + H was managed without mechanical practices and the plots managed with CT were tilled with a cultivator in spring followed by tine and disc harrowing in summer (25 cm) to diminish the sizes of soil clods.

4.1.2.3. Sampling and analysis

Soil samples were collected in February 2004 in CT0 and in February 2019 in CT1 and NT1 + H. Pits were dug with a mini-excavator and soil samples were collected along the different soil horizons using a hand trowel. Five soil profiles were sampled in each plot (5 soil profiles × 3 plots = 15 complete soil profiles).

In the laboratory, all samples were air-dried and passed through a 2-mm sieve to remove gravel and roots. The preliminary analyses were realised in 2004 for CT (CT0) and the second analyses were realised in 2019 for NT1 + H and CT (CT1). Soil properties were studied at different depths taking into account the soil profile, horizon by horizon, instead of by soil control sections, because soil depth is crucial to understanding the distribution and redistribution of SOC and, therefore, the total SOC stock (SOC-S). The analytical methods are described in Table 2.

Parameters	Method
Field measurements	
Bulk density (Mg m^{-3})	Cylindrical core sampler [a]
Laboratory analysis	
Particle size distribution	Bouyoucos method (USDA, 2004) [b]
pH-H_2O	Suspension in water 1:2.5 (Guitián and Carballas,1976)
Total Nitrogen (g kg^{-1})	Kjeldahl method (Bremner, 1996)
Soil Organic Carbon (g kg^{-1})	Walkley and Black method (Nelson and Sommers, 1982)

Table 2. Analytical methods used in this study.
[a] 3 cm in diameter, 10 cm in length and 70.65 cm^3 in volume.
[b] Prior to determining the particle size distribution, samples were treated with H_2O_2 (6%) to remove organic matter (OM). Particles larger than 2 mm were determined by wet sieving and smaller particles were classified according to USDA (2004).

Data were tested for normality to verify the model assumptions using the Shapiro-Wilk test. As the data failed the normality test, non-parametric tests were used (Kruskal-Wallis ANOVA). Differences of $p < 0.05$ were considered statistically significant. All computations were made using SPSS 13.0 for Windows.

4.1.3. Results and discussion.

4.1.3.1. General soil properties.

In the olive grove studied, the analysed soils were classified as Calcaric Cambisols according to the IUSS Working Group WRB (IUSS-ISRIC-FAO, 2015). Soil properties were studied at a similar thickness so that comparisons between soil profiles would be easier. Table 1 shows the main soil physical-chemical properties of the soils studied. Concerning soil thickness, there were no significant variations in the analysed period (15 years) for both land management [NT1 + H (110 cm) and CT1 (119.7 cm)] relative to the initial situation [CT0 (115.7 cm)]. Regarding the analysis of the different horizons thickness, the main variation could be observed in the depth of the surface horizon (A horizon) whereas CT1 slightly increased its thickness (32.7 cm), while NT1 + H reduced its strength (21.7 cm) relative to the initial situation (27.3 cm). The profiles opened in the study area showed a cambic B horizon on the subsurface with thicknesses from 60 to 80 cm. This horizon presented evidence of alteration with bedrock that allows us to differentiate between two types Bw and BC according to the degree of alteration. Subsurface horizons characteristics and their physical and chemical properties are of great importance in the development of permanent woody crops such as olive trees because in areas of the Mediterranean basin with low and irregular rainfall they can act as water reservoirs during the dry months and drought periods (Torrent, 2005). Therefore, deeper soils sampling and analysis are crucial to know the crop-soil interrelations in the study area.

As an indicator of soil development processes, soil texture is a critical factor. The main characteristic of these analysed soils was the high levels of clay observed under all managements and horizons (Table 1). The highest values in clay size were found in CT0 and CT1, with quite homogeneous levels (around 70%) in both cases and all horizons. However, there was a reduction if we compare these data with those obtained in the NT1 + H system, which became less clayey, remaining at 60% in all the horizons except in the C horizon, which was close to 70%. This is a relevant property of these soils due to clay substrates having a high potential to hold water (Tolk, 2003) but also a high permanent wilting point. Therefore, the available water decreases with increasing clay content. In addition, many studies have found a significant correlation between organic carbon and clay content (Arrouays *et al*., 2006; Plante *et al*., 2006; Mohsin Abrar *et al*., 2020). On the contrary, the silt class had significantly ($p < 0.05$) higher percentages in the NT1 + H treatment above 25% in the A horizon where the NT1 + H obtained 26.7%, CT0 was 19.8% and CT1 was 19.1%. As can be seen in Table 1, the sand size class obtained the lowest percentages within the textural class of this soil. All treatments and horizons contained low percentages in sand fractions, and these values were below 13%. In this fraction, the main difference between management types was found under the NT1 + H treatment in the Bw horizon where the highest values were obtained (12.9%).

The percentage of gravel remained at quite similar values between managements with low and medium gravel contents ranging from 12.8%

to 21.7%. The gravel content in the surface horizons could be associated with losses of small soil particles mainly through erosion processes while, as shown in other studies (Poesen *et al*., 1999; Cerdà, 2001; Rodrigo-Comino *et al*., 2017), gravel and rock fragments have a higher resistance to these processes. In this sense, in some studies, gravel has been taken as a key factor in estimating soil erodibility and erosion rates (Hu *et al*., 2019). This process could have important effects on soil quality and decreases the agronomic productivity of soil (Lal, 1998). In this sense, many studies have indicated that soil erosion is the main environmental issue associated with olive production (Fleskens and Stroosnijder, 2007; Palese *et al*., 2015; Sastre *et al*., 2017). The highest gravel content values were obtained in the BC horizon under all managements. In this horizon, the percentage of gravel was around 20%.

As shown in Table 1, bulk density (BD) values were in the range of 1.35–1.44 Mg m^{-3}. The lowest values were found in the surface horizon in all profiles reaching average values of 1.37 Mg m^{-3}, and generally, BD increased in depth. Several studies have reported that in the upper 30 cm soil layer, the BD under the absence of tillage was superior to the BD of tilled soil (Puget and Lal, 2005; Martínez-Mena *et al*., 2013; Gál *et al*., 2007), However, other research has indicated the opposite tendency (Ussiri and Lal, 2009; Du *et al*., 2010); therefore, soil BD was similar or smaller under NT1 + H relative to tilled management. These high BD values for both managements involved considerable levels of soil compaction, which influenced the lower soil aeration, water retention and infiltration rates (FAO, 2006). In addition, soil compaction promoted runoff processes and soil and nutrient losses, increasing soil erosion rates and influencing the SOC-S evolution (Abbas *et al*., 2020).

When pH was compared, there generally were no significant differences ($p < 0.05$) relative to land management (NT1 + H or CT) and sampling period (CT0 or CT1). The pH values were between 7.72 and 8.09 in all cases, and the same trend was found for all treatments, where the values increased overall from the surface horizon to the subsoil due to a higher carbonate accumulation. These high values could be associated with climatic conditions, parent material lithology rich in calcium carbonate and poor OM concentrations (Rezaei and Gilkes, 2005).

4.1.3.2. Tillage and no-tillage effects on soil organic carbon concentration.

In the studied area, the SOC concentrations were relatively low in all the horizons and analysed periods, not exceeding 6.5 g kg $^{-1}$ in the examined samples in any circumstance (Figure 3). These low values appear in the majority of olive grove soils in the Mediterranean basin, where both the intensive cultivation and land degradation result in SOC losses due to the lack of biomass residues, which increases the entrance of SOC in the agroecosystem and causes low levels of OM (Verheye and De la Rosa, 2005; Hernanz *et al*., 2009; Cerdà *et al*., 2010).

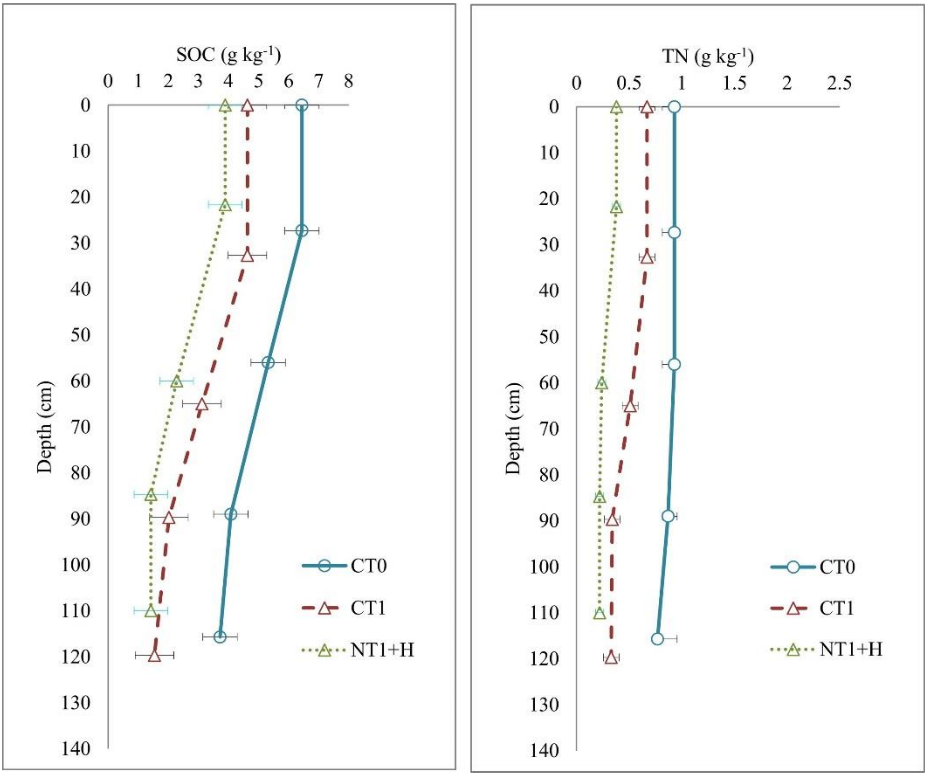


Figure 3. SOC and TN concentration in CT0 (preoperational stage), CT1 and NT1 + H (both final stage) in the studied area. SOC: Soil organic carbon; NT: Total nitrogen; CT0: Conventional tillage; CT1: Conventional tillage NT1 + H: No tillage; (average ± SD).

SOC losses were registered over time due to CT0 (sampled in 2004) obtaining the highest SOC concentration values in all analysed horizons compared to CT1 and NT1 + H (sampled in 2019) (Figure 3). In this study, the lowest levels of SOC concentration were found under the NT1 + H treatment. This management lost 56% of SOC on average in the different horizons regard to the initial situation. On the other hand, CT1 obtained lower values than in the previous sampling (2004), although the losses of SOC were lower than in the NT1 + H treatment, 45% on average. Therefore, there was a loss of SOC during the period from the first measurements in 2004 to the following ones, in 2019, in both treatments and all horizons. Although it is accepted that sustainable agricultural practices improve SOC levels over time (Morugán-Coronado *et al*., 2019), the decline in SOC in long term agricultural soils has been widely reported even when reduced or NT practices were applied in cropland soils (Luo *et al*., 2010; Beretta-Blanco *et al*., 2019). These studies identified that among the main factors of this decline in SOC were the intensification of agriculture (Powlson *et al*., 2011; Kopittke *et al*., 2019), the continuous tillage, the maintenance of bare soils and high erosion rates (Lal, 2010). Consequently, NT1 + H not only did not increase the levels of SOC across the soil profiles but also resisted losses during the analysed period significantly worse than CT1 the SOC in the study area. Therefore, changes in land management systems directly affected soil SOC content (Guo and Gifford, 2002; Aguilera *et al*., 2013; Vicente-Vicente *et al*., 2016) but not in the direction that the vast majority of the literature developed in this field indicate. This trend was because in our study area under the NT1 + H system, the absence of plant cover and the continuous maintenance of bare soil through the application of herbicides caused crusting processes and promoted high erosion rates and SOC losses. Therefore, agricultural management that involves the maintenance of plant cover seems to be necessary for the reduction of SOC losses.

Focusing the attention on the A horizon, the SOC concentration was significantly affected in the period from the initial sample collection

(2004) to the final sample collection (2019) (Figure 3). According to this analysis, the highest SOC values were obtained in CT0 (6.4 g kg^{-1}), significantly decreasing ($p < 0.05$) SOC concentrations in both treatments although the values were slightly higher under the CT1 treatment compared to the NT1 + H treatment (4.6 *vs* 3.9 g kg $^{-1}$) within the A horizon. Therefore, CT1 showed higher resistance to the SOC loss than NT1 + *H. Major* resistance could be attributed to a higher input of SOC in CT1 due to the inclusion of pruning remains and mineral fertiliser (Kundu *et al*., 2007; López-Garrido *et al*., 2014), in the arable horizon by ploughing (Badagliacca *et al*., 2018), while under the NT treatment, there was no soil disturbance, and pruning remains and mineral fertiliser were maintained at the soil surface. Through ploughing, surface crusting problems were solved under CT1 management, while in the NT1 + H treatment, this problem was aggravated by the herbicide application.

This surface disposition of C-rich elements causes a higher loss either to transport of organic material through water erosion or mineralisation of OM (Oorts *et al*., 2006) turning to soluble inorganic or gaseous forms (CO_2) which are emitted to the atmosphere (Smith, 2008). Crop residues were the main source of SOC in the study area and included small branches, shoots, leaves and other plant parts that remained after harvest. Crop residues contain approximately 45% carbon and are the main precursors of OM (Jarecki and Lal, 2003; Porta *et al*., 2003). Many authors have pointed out the benefits associated with the return of crop residues to the soil in improving soil structure, soil water-holding capability and soil erosion prevention and their possible use in the increase of SOC in several types of soil and with diverse types of crops (Lal, 2009; Liska *et al*., 2014; Zhang *et al*., 2015; Pu *et al*., 2019). However, as discussed above, in this area the crop residues magnitude was not enough to prevent SOC loss.

Many studies have reported a superficial increase in SOC concentration by changing the management practices from CT to NT in different cropping systems and climates, applying herbicides (Mazzoncini *et al*., 2011; Aguilera *et al*., 2013; Alvarez *et al*., 2014) and not applying them (Palese *et al*., 2014; Almagro *et al*., 2017). Even these findings were also obtained in Mediterranean semiarid conditions in Spain (Ordóñez-Fernández *et al*., 2007; Virto *et al*., 2007; Álvaro-Fuentes *et al*., 2008). The SOC increments under NT are frequently measured in the first few centimetres of soil (Dolan *et al*., 2006; Yang *et al*., 2008; Ferreira *et al*., 2013a; Álvaro-Fuentes *et al*., 2014; Du *et al*., 2017), while if we analyse the complete soil profile, those increments are generally lower or even disappear in favour of reduced tillage or CT management (Luo *et al*., 2010). In this study, this superficial increase in SOC concentration that is usually measured under the NT1 + H system was not observed, since the first horizon was sufficiently thick for this effect not to be appreciated and the herbicide application kept the soil bare and thus limited the OM inputs. Therefore, one of the reasons for the lack of an increase in SOC in the surface horizon after 15 years under the NT1 + H system is that it normally is restricted only to shallow depths.

4.1.3.3. Tillage effects on total nitrogen concentration.

Soil TN concentration showed a similar trend to that followed SOC values, taking into account the whole profile where the highest values were found in CT0 (Figure 3). In this case, the decrease in TN concentration for NT1 + H management was even greater than in SOC concentration, with a loss of 70% on average in the different horizons, while for CT1, the variation was 48% less on average relative to the initial situation. This significant loss of soil fertility during the 15-year study period was associated with the losses of SOC due to the processes mentioned above and the natural extraction of the olive grove to produce its harvest where it is estimated that olive trees need between 15 and 20 kg of nitrogen per 1000 kg of olive yield (MAGRAMA, 2012). Moreover, the maintenance of bare soil and the absence of a significant amount of crop residue (pruning residues every two years) or mulch caused decreased soil nutrition and increased soil degradation (Blanco-Canqui and Lal, 2008; Colazo and Buschiazzo, 2015). In this sense, some estimates indicate that residues could provide between 18 and 62 kg Mg^{-1} nutrients to the soil, depending on the type of residue (Lal, 2009). In semiarid areas, plant cover is necessary to conserve OM and nutrients in olive orchards (Durán-Zuazo *et al*., 2009).

Therefore, tillage had significant influences on TN concentration, and CT1 showed higher values compared to NT1 + H. Some researchers have reported a lower impact of NT in TN concentration in deeper layers (Angers *et al*., 1997; Gál *et al*., 2007; Vazquez *et al*., 2019); however, other many long term studies in Mediterranean conditions have found the inverse conclusions in cereal crops (Mazzoncini *et al*., 2016), fava bean crops (Badagliacca *et al*., 2018) or different types of cover crop species (Mazzoncini *et al*., 2011). Others have not found a significant effect in cereals/legumes rotation (Laghrour *et al*., 2016). These variations in the results and conclusions regarding the evolution in long periods of TN could be associated with the differences in climatic conditions, the management carried out in cover under NT treatment (Varvel and Wilhem, 2011) and the type of soil or the crop that was examined.

In all periods and managements, TN tended to decrease with depth; therefore, the highest values were found in the A horizon, where CT0 reached $0.93\ g\ kg^{-1}$, CT1 reached $0.67\ g\ kg^{-1}$ and NT1 + H reached $0.38\ g\ kg^{-1}$ (Figure 3). In the surface horizon, the reason for the lowest levels of TN under NT1 + H was probably due to the high temperatures of the study area. These temperatures were caused in uncovered soils, and under NT + bare soil, there was a higher nitrogen liberation (Palma *et al*., 1998; Liang *et al*., 2016). This occurs with the exposure of OM to environmental factors from its maintenance on the soil surface (Oorts *et al*., 2006) and soil crusting that takes place in the dry areas under Mediterranean conditions when NT is installed due to the low OM content, leading to low N availability in the soil (López-Garrido *et al*., 2014; Martínez-Mena *et al*., 2013).

In both final situations (CT1 and NT1 + H), the same trend in TN was detected in the subsurface horizons (from Bw to C), with significant losses of TN levels from the CT0 treatment, with 0.93, 0.87 and 0.77 $g\ kg^{-1}$ (in Bw, BC and C, respectively) to CT1, with 0.51, 0.34 and 0.33 $g\ kg^{-1}$ (in Bw, BC and C, respectively) and NT1 + H, with 0.24, 0.22 and 0.22 $g\ kg^{-1}$ (in Bw, BC and C, respectively) (Figure 3). Therefore, as it has been analysed in the evolution of management systems and according to Bronick and Lal (2005) and Pulleman *et al*. (2005), as well as SOC, TN losses were registered over time due to CT and NT with bare soil decreasing the SOC and NT content because these systems reduced the annual rate of organic amendments and soil aggregate stability and enhanced the risks of erosion and soil aeration. These results in SOC and TN concentrations were in line with other study cases, such as Hernández *et al*. (2005) and Castro *et al*. (2008), who when also studying an olive grove in Spain (Toledo and Jaén), found the lowest SOC and TN concentration under NT with the use of glyphosate herbicide treatment compared to CT and NT with cover management.

The relationship between the carbon and nitrogen (C:N) content determines the rate at which the OM in the soil decomposes and therefore the availability of nitrogen for the olive grove. The studied area showed values of C:N ratios always below 11 (Table 1) and the greatest values were found at the upper horizon for all treatments. In comparison with CT0 ($C:N = 7$ in Ap and $C:N = 5.7$ in Bw), the NT1 + H treatment significantly increased ($p < 0.05$) the soil C/N ratio in the first two horizons to 10.2 (A) and 9.5 (Bw), while CT1 obtained slightly lower values of 6.1 (Ap) and 5.1 (Bw). However, in deeper horizons (BC and C), CT1 and NT1 + H obtained similar values, and the C:N ratio increased relative to the initial situation. These results showed a trend demonstrated in other studies where the conservation tillage system leads to higher C:N ratios although the input residues restricted to the first few centimetres of the surface (Blanco-Canqui and Lal, 2008; Lou *et al*., 2012;). Other experiments have shown that high clay content is frequently associated with more decomposed OM and lower C:N ratios (Puget and Lal, 2005; Ouédraogo *et al*., 2006; Yamashita *et al*., 2006; Parras-Alcántara *et al*., 2013).

As expected, SOC concentrations gradually decreased from the soil surface to deeper soil horizons, between 110 and 120 cm, for all treatments (Figure 3). In the Bw horizon, the trend observed on the upper horizon continued. There was a higher value for CT0 (5.3 g kg $^{-1}$) followed by CT1 and NT1 + H with lower values, 3.1 and 2.3 g kg $^{-1}$ respectively (Figure 3). In this horizon, the losses relative to the initial situation were even higher than in the surface horizon, with a decrease of 41% for CT1 and 57% for NT1 + H. The higher decline in SOC concentration in this horizon could be mainly attributed to the limited effect of pruning remains inputs even more limited than the upper horizon because the BW horizon was found at approximately 30 cm from the surface for CT and 20 cm for NT1 + H. In this sense, CT1 and NT1 + H lost 32% and 41% of their SOC concentrations, respectively, compared to the upper horizon, while CT0 decreased by 17%. Therefore, deeper horizons depend on SOC inputs in the upper horizons because subsoil receives OM inputs in the form of fine roots, root exudates, and dissolved organic carbon (Michalzik *et al*., 2001; Angst *et al*., 2018) and are abundant in microbial-derived OM compounds compared to the surface horizon, (Castellano *et al*., 2015; Mohsin Abrar *et al*., 2020). Similar SOC concentrations were obtained in the two deepest horizons (BC and C), where the main differences were found regarding the initial situation. In the CT0 treatment, SOC concentrations of 4.1 and 3.7 g kg^{-1} were measured in these horizons respectively; in CT1 the measurements were 2 and 1.5 g kg^{-1} and in NT1 + H, the measurements were 1.4 g kg^{-1} in both horizons (Figure 3). These results are in line with other previous studies where the similarity in SOC concentration at subsoil layers under CT practices and reduced tillage or NT has been demonstrated (Baker *et al*., 2007; Dimassi *et al*., 2014; Powlson *et al*., 2014).

In line with what was mentioned above, the OM percentages (Table 1) remained at low levels, ranging in the analysed profiles between 1.22–0.71 (CT0), 0.88–0.29 (CT1) and 0.74–0.27 (NT1 + H), and they suffered a significant decrease in CT1 (44.6% on average) and NT1 + H (55.8% on average) relative to CT0. Low OM levels imply a greater vulnerability to erosive processes due to the lack of soil structure. In this sense, OM is an essential element in the soil particle aggregation processes (Garcia-Franco *et al*., 2015) and water retention that is especially relevant in areas such as the Mediterranean basin, where long drought periods alternate with strong storms and woody crop productivity is constrained by soil water availability (Martínez-Mena *et al.*, 2013).

4.1.3.4. Soil organic carbon and Total nitrogen stock.

In the long-term period analysed, the total soil retention of C reached values from 68.1 Mg ha^{-1} in CT0 to 39.9 Mg ha^{-1} in CT1 and 39.8 Mg ha^{-1} in NT1 + H (Figure 4). These values are within the observed range in other studies carried out in olive grove systems (Parras-Alcántara and Lozano-García, 2014; Fernández-Romero *et al*., 2016). Total SOC-S in the studied area decreased by 41% under CT1 and NT1 + H. Consequently, after 15 years under both management systems, there has been a significant soil decarbonisation process (−1.8 Mg C ha^{-1} yr^{-1}). In this case, NT1 + H not only did not increase SOC storage but also resisted the SOC-S depletion worse than CT1 in the analysed period. Therefore, it is necessary to specify under which management practices (cover crops, residue amount and organics amendments, among others) NT modifies SOC-S trajectory relative to CT without detriment to crop profitability and becomes an efficient practice for carbon sequestration. In this study, management under NT with herbicide application and bare soil was shown to be an unsustainable management practice. Furthermore, in Andalusian olive groves, many farmers have considered NT with bare soil by the application of herbicides (to avoid water competition between olive trees and weeds) as a sustainable option for the management of their crops and an improvement in the quality of their soil properties since NT eliminates continuous tillage and reduces agricultural labour. It is therefore necessary to analyse these management techniques in detail and propose sustainable alternative systems.

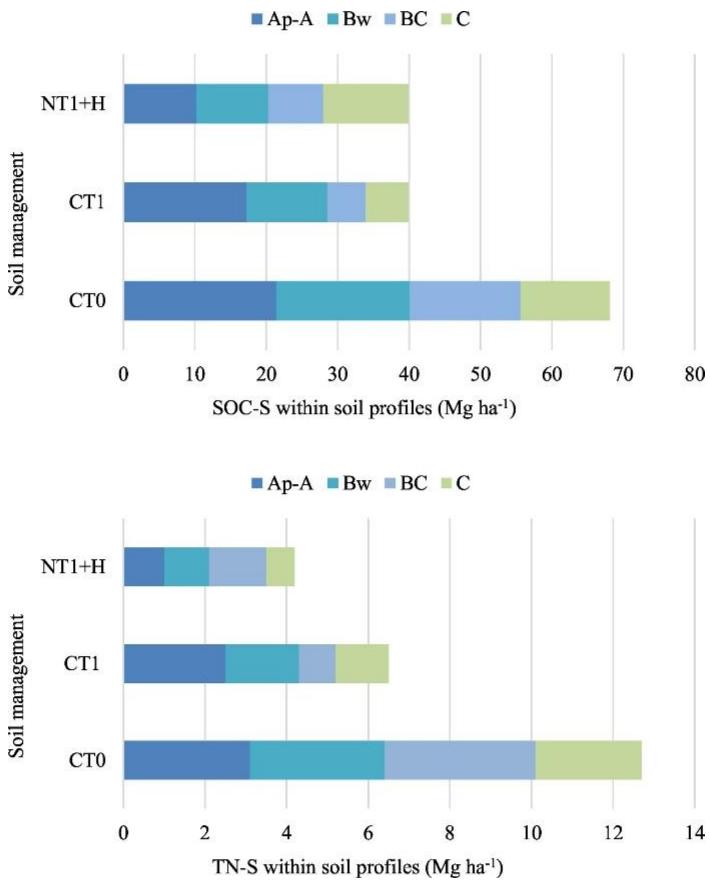


Figure 4. SOC-S and NT-S in CT0 (preoperational stage), CT1 and NT1 + H (both final stage) in the studied area. SOC-S: Soil organic carbon stock; NT-S: Total nitrogen stock; CT0: Conventional tillage; CT1: Conventional tillage NT1 + H: No tillage; (average ± SD).

The results of this study implied that taking into account the complete soil profile, SOC-S obtained the greatest values in the subsoil horizons (below 20–30 cm) and decreased in depth overall (Figure 4). While in the initial situation, the Ap horizon contained 31.5% of the C stored in the soil (21.4 Mg ha^{-1}), after 15 years, this upper horizon increased its relevance within the percentage of SOC-S content of the soil profile reaching 43.5% (17.3 Mg ha^{-1}) under CT1; while under NT1 + H, it descended to 25.6% (10.2 Mg ha^{-1}). However, in our experiment, despite these variations during the long-term period analysed, values showed that the highest contents in SOC-S were found in the subsoil horizons (Bw, BC and C horizons) and demonstrated that the potential storage of these horizons may be higher than those of the surface horizons (Chenu *et al*., 2019). This fact is especially relevant since according to Balesdent *et al*. (2017), the average global residence time of SOC is approximately four times higher in the subsoil (30–100 cm deep) than in the top layer of the soil (0–30 cm). Therefore, it is relevant to emphasise that under both management systems there was a deterioration of carbon storage, and the decarbonization process has not only degraded the soil nutritional properties but also has involved an additional C transfer from the soil to the atmosphere even from the most resistant horizons to maintain C budget. Currently, the implementation of agricultural practices that can create a positive C budget to promote the C sequestration and restoration of the soil C pool is an essential challenge for these agricultural systems since they play a fundamental role in the global C cycle (Lal, 2016.)

In the present study, comparing the two management sequences, we can observe that CT1 maintained better levels of SOC-S in the upper horizon where there was not great reduction regard to the initial situation (−4.1 Mg ha^{-1}). However, in the deeper horizons, the CT1 treatment lost a large quantity of SOC-S (−29.3 Mg ha^{-1}). On the other hand, the

NT1 + H treatment better resisted the C loss in the two deepest horizons (−8.4 Mg ha^{-1}). However, in the upper horizons, the NT1 + H treatment suffered greater SOC-S losses (−19.8 Mg ha^{-1}) (Figure 4). These results showed that in long term CT maintained similar SOC-S levels in the first horizon, fundamentally due to the incorporation of OM through tillage below the first centimetres; nevertheless, the deterioration of deeper horizons was higher. Under the NT1 + H system, SOC-S values in the first two horizons were diminished due to the reduction in the C inputs since the organic material remained on the surface and the crusting process made more difficult the soil C inputs although the lower aeration of the horizons and lack of mechanical disruption to soil aggregates allowed greater stability of SOC-S in deeper horizons (González-Rosado *et al*., 2020b). In the final stage, the SOC-S was quite similar under both management systems, indicating that in the strategy to achieve a positive C budget and SOC sequestration, the vegetation coverage would be a crucial factor and could have a greater influence than tillage or no-tillage.

The results of our study demonstrated the importance of the analysis of C sequestration in deeper horizons in woody crops. It is essential to determine the impact of management practices implemented; for example, in this study, if our data had been analysed only from the first horizon, different conclusions would have been reached.

Regarding TN-S (Figure 4), the values followed a similar tendency to that determined for SOC-S. In this parameter, the decreases detected (taking into account the complete soil profile) were higher than those that were found for SOC-S. The losses in the CT1 treatment were 48.8% (6.5 Mg ha^{-1}) and in the NT1 + H treatment, and they were 66.9% (4.2 Mg ha^{-1}) compared to the initial situation (CT0) of 12.7 Mg ha^{-1}. These results represent a loss of −0.57 Mg N ha^{-1} yr^{-1} under NT1 + H and − 0.41 Mg N ha^{-1} yr^{-1} under CT1, which means significant nutritional deficits in the soil annually. Nitrogen deficits are replaced by fertiliser inputs, in this study case inorganic fertiliser, which implies an important cost for farmers and a significant contribution of agricultural systems to climate change (EEA, 2019).

4.1.3.5. 4‰ initiative: the soil recarbonisation.

In recent years, soil carbon sequestration and storage, *i.e.* the process of transferring CO_2 from the atmosphere into the soil and its retention in time (Chenu *et al.*, 2019) have generated a wide literature. This documentation is mainly related to the 4‰ initiative, which has promoted a space for discussion and a large variety of strategies within the scientific community and policymakers (Rumpel *et al.*, 2019).

The lack of specific long term case studies has been seen as a weakness (Francaviglia *et al.*, 2019) among others (Poulton *et al.*, 2017; Rumpel *et al.*, 2019) when implementing strategies to achieve the objectives of the 4‰ initiative reach a 4‰ annual growth rate of SOC-S in the top 40 cm of soils (0.4% per year). In our olive grove studied, with bare soil and herbicide application has not achieved the 4‰ objectives after 15 years under NT. Similar conclusions were obtained in Francaviglia *et al.* (2019) where NT with bare soil and herbicide application was determined as the worst practice management option for SOC storage in woody crops under the Mediterranean climate. Thus, applying the per 1000C storage formula (Francaviglia *et al.*, 2019) the losses of SOC-S during the analysed period were − 27.6 Mg C ha^{-1} yr^{-1} × 1000 for both management methods when taking into account the entire profile (Figure 5).

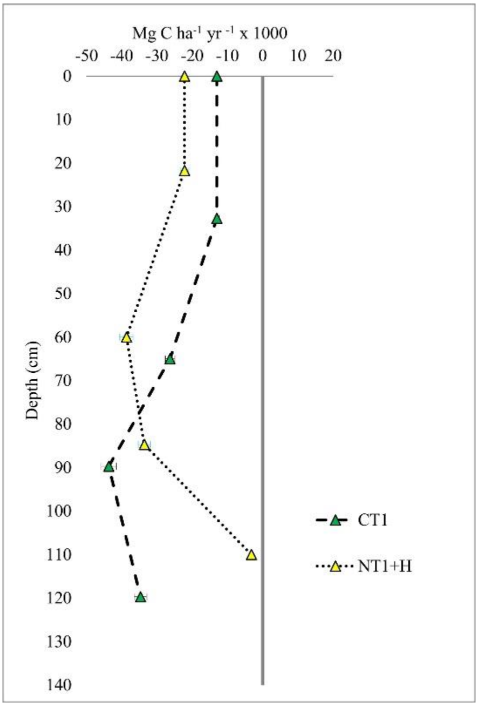


Figure. 5. Per 1000C storage rate based on the duration of the experiment in years for CT1 and NT1 + H (final stage) compared to CT0 (preopeartional stage). Line at level 0 represents the initial content (average ± SD).

A relevant aspect in this debate is that the depth of reference soil to use to evaluate the success of the objective of this initiative has created uncertainties (Chabbi *et al*., 2017; Poulton *et al*., 2017). In this sense, the 4‰ initiative refers to increases in SOC-S in a depth of 40 cm, excluding deeper horizons. Applying this reference to our case study, if we only take as a reference the A horizon, the CT1 management obtained lower losses since SOC-S inter-annual decrease was estimated at 1.3% (−12.9 Mg C ha^{-1} yr^{-1} × 1000) over 15 years (Figure 5), and in this same horizon under NT1 + H, the values were also negative −3.5% (−34.9 Mg C ha^{-1} yr^{-1} × 1000). On the contrary, taking into account the complete soil profile (below 100 cm) the SOC-S resulting from the NT1 + H treatment continued with a negative percentage (−2.7%), and under the CT1 treatment, the same direction of the trend continued over the 15 years, resulting in a − 2.7% annual SOC-S loss and, therefore, would not achieve the targets established by the 4‰ initiative. The soil thickness to consider and the number of years to study are critical aspects to evaluate the effectiveness of the actions adopted to achieve a 4‰ increase in carbon storage. In our case study, it was demonstrated that the exclusion of deeper horizons in the measurement of the implemented management practices could lead to overestimates in carbon capture and storage and, therefore, erroneous conclusions that could be accepted as feasible management practices that do not truly encourage carbon sequestration. In line with these observations, recent studies under perennial crops (Bateni *et al*., 2019; Ledo *et al*., 2020) highlight the relevance of SOC stored at deeper horizons (>30 cm) and recommend considering a profile of 0–100 cm as a reference for SOC-S since only considering the top 30 cm would encourage practices and crops that concentrate SOC in the surface horizon when more stable SOC was related to deeper soil layers (Abbas *et al*., 2020).

To achieve the 4‰ targets and reverse the imbalance in the SOC-S, the equilibrium between SOC inputs and outputs must be modified. According to Rumpel *et al*. (2019), it is necessary to improve management practices in agricultural systems to recycle carbon back into the soil. In this sense, Vicente-Vicente *et al*. (2017) estimated in similar areas that spontaneous cover was a source of C (0.56 t C ha^{-1} yr^{-1}). However, C inputs through the vegetation cover that depend on the net primary production can be extremely variable over time in the Mediterranean areas and especially in rain-fed olive groves (Vicente-Vicente *et al*., 2017) with spontaneous vegetation cover. Even with sown cover, aboveground biomass production can be highly variable, so these C increases will depend largely on soil properties and climatic conditions of the area and year (Hernández *et al*., 2005; González-Rosado *et al*., 2020a). In this sense, the expected increase in temperature and rainfall reduction because of climate change in the Mediterranean basin (Lionello and Scarascia, 2018) may affect this strategy due to decreased photosynthesis rates, crop biomass development and crop productivity, with a consequent lower return of aboveground biomass to the soil. Therefore, in line with Muñoz-Rojas *et al*. (2015), future climatic scenarios can negatively affect SOC-S in the upper soil sections.

Despite these future projections, soils that have been historically depleted have great carbon storage potential (Minasny *et al*., 2017). The highest soil C sequestration rate observed in olive orchards was estimated at 5.3 t C ha^{-1} yr^{-1} (Vicente-Vicente *et al.*, 2016). Therefore, there is a great potential for carbon sequestration, and olive grove areas in the Mediterranean region could become important C reservoirs since 9.5 million ha of olive groves are located in this region (Nieto *et al.*, 2013). With the application of efficient practices, the 4‰ initiative goals could even be surpassed (Minasny *et al.*, 2017), changing olive grove soils from sources of carbon emissions (decarbonisation) to carbon sink areas (recarbonisation). Olive orchards have a significant SOC storage capacity and therefore have the potential to mitigate climate change. To achieve this, it is necessary to define which management options on a local scale are ideal for increasing carbon stocks over time. Following the analysis of this study, CT1 and NT1 + H were not management systems under which the objectives defined in the 4‰ initiative could be achieved. In this sense, management options such as cover crops (Nieto *et al.*, 2012; Palese *et al.*, 2014), intercropping (Morugán-Coronado *et al.*, 2019), animal inclusion in the farm and agroforestry systems (Álvarez *et al.*, 2007; Ferreira *et al.*, 2013b; Wiesmeier *et al.*, 2020) have shown that they can be useful management options to reach 4‰ goals, thereby contributing to mitigating climate change, adapting to climate change and increasing food security.

4.1.4. Conclusions.

In olive groves, NT1 + H management with bare soil was shown to be an unsustainable agricultural practice to achieve the 4‰ targets after

15 years of study. The NT1 + H treatment showed high rates of SOC-S and TN depletion in the analysed profiles and the CT1 management also showed a similar SOC-S and TN loss when considering the complete soil profile. However, if only the first horizon had been analysed, the results showed significant differences between the two managements. Furthermore, the exclusion of deeper horizons in the analysis of the implementation of 4‰ initiative in woody crops could lead to incorrect decisions when choosing the management practices that better adapt to local conditions to increase SOC-S. Therefore, this research showed that for SOC-S assessment in woody crops, the analysis of deep horizons was highly relevant since they can be potentially important C reservoirs.

4.1.5. References.

Abbas, F., Hammad, H., Ishaque, W., Farooque, A., Bakhat, H., Zia, Z., Fahad, S., Farhad, W., Cerdá, A., 2020. A review of soil carbon dynamics resulting from agricultural practices. J. Environ. Manag. 268. 110319. https://doi.org/10.1016/j.jenvman.2020.110319

Aguilera, E., Lassaletta, L., Gattingerd, A., Gimenoe, B., 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. Agric., Ecosyst. Environ. 168, 25–36. https://doi.org/10.1016/j.agee.2013.02.003

Almagro, M., Garcia-Franco, N., Martínez-Mena, M., 2017. The potential of reducing tillage frequency and incorporating plant residues as a strategy for climate change mitigation in semiarid mediterranean agroecosystems. Agric. Ecosyst. Environ. 246, 210–220. https://doi.org/10.1016/j.agee.2017.05.016.

Alvarez, C., Alvarez, C.R., Costantini, A., Basanta, M., 2014. Carbon and nitrogen sequestration in soils under different management in the semi-arid Pampa (Argentina). Soil Till. Res., 142, 25-31. https://doi.org/10.1016/j.still.2014.04.005

Álvarez, S., Soriano, M.A., Landa, B.B., Gómez, J.A., 2007. Soil properties in organic olive groves compared with that in natural areas in a mountainous landscape in southern Spain. Soil Use Manag. 23, 404–416. https://doi.org/10.1111/j.1475-2743.2007.00104.x.

Álvaro-Fuentes, J., Plaza-Bonilla, D., Arrue, J.L., Lampurlanes, J., Cantero-Martinez, C., 2014. Soil organic carbon storage in a no-tillage chronosequence under Mediterranean conditions. Plant Soil, 376, 31-41. https://doi.org/10.1007/s11104-012-1167-x

Álvaro-Fuentes, J., López, M., Cantero-Martínez, C., Arrúe, J., 2008. Tillage effects on soil organic carbon fractions in Mediterranean Dryland Agroecosystems. Soil Water Manage. Conserv. 72, 541–547. https://doi.org/10.2136/sssaj2007.0164

Andreu-Lara, C., Delgado, B., Ojeda Rivera, J.F., Infante Amate, J., 2013. Los olivares andaluces y sus paisajes distintivos del mundo mediterráneo. Revista de estudios regionales 96, 267-291.

Angers, D.A., Bolinder, M.A., Carter, M.R., Gregorich, E.G., Drury, C.F., Liang, B.C., Voroney, R.P., Simard, R.R., Donald, R.G., Beyaert, R.P., Martel, J., 1997. Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. Soil Till. Res. 41, 191–201. https://doi.org/10.1016/S0167-1987(96)01100-2

Angst, G., Messinger, J., Greiner, M., Häusler, W., Hertel, D., Kirfel, K., Kögel-Knabner, I., Leuschner, C., Rethemeyer, J., Mueller, C.W., 2018. Soil organic carbon stocks in topsoil and subsoil controlled by parent material, carbon input in the rhizosphere, and microbial-derived compounds. Soil Biol. Biochem. 122, 19–30. https//doi.org/10.1016/j.soilbio.2018.03.026

Arrouays, D., Saby, N., Walter, C., Lemercier, B., and Schvartz,C., 2006. Relationships between particle-size distribution and organiccarbon in French arable topsoils, Soil Use Manage. 22, 48–51. https://doi.org/10.1016/j.soilbio.2018.03.026

Balesdent, J., Basile-Doelsch, I., Chadoeuf, J., Cornu, S., Fekiacova, Z., Fontaine, S.,Guenet, B., Hatté, C., 2017. Renouvellement du carbone profond des sols cultivés: une estimation par compilation de donnéesisotopiques. Biotechnol. Agron. Soc. Environ. 1–12.

Badagliacca, G. E., Benítez, G., Amato, L., Badalucco, D., Giambalvo, V.A., Laudicina, P. R., 2018. Long-term no-tillage application increases soil organic carbon, nitrous oxide emissions and faba bean (*Viciafaba*L.) yields under rain-fed Mediterranean conditions. Sci. Total Environ. 639, 350-359. https://doi.org/10.1016/j.scitotenv.2018.05.157

Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffs, T.J., 2007. Tillage and soil carbon sequestration—What do we really know? Agric. Ecosyst. Environ. 118, 1–5. https://doi.org/10.1016/j.agee.2006.05.014

Bateni, C., Ventura, M., Tonon, G., Pisanelli, A., 2019. Soil carbon stock in olive groves agroforestry systems under different management and soil characteristics. Agroforest Syst. https://doi.org/10.1007/s10457-019-00367-7.

Beretta-Blanco, A., Pérez, O. Carrasco-Letelier, L., 2019. Soil quality decrease over 13 years of agricultural production Nutr. Cycl. Agroecosyst. 3, https://doi.org/10.1007/s10705-019-09990-3

Blanco-Canqui H., Lal R., 2008. No-tillage and soil-profile carbon sequestration: An on-farm assessment. Soil Sci. Soc. Am. J. 72, 693–701. https://doi.org/10.2136/sssaj2007.0233

Bronick, C.J., Lal, R., 2005. Manuring and rotation effects on soil organic carbon concentration for different aggregate size fractions on two soils in northeastern Ohio, USA. Soil Till. Res. 81, 239– 252. https://doi.org/10.1016/j.still.2004.09.011

Castellano, M.J., Mueller, K.E., Olk, D.C., Sawyer, J.E., Six, J., 2015. Integrating plant litter quality, soil organic matter stabilization, and the carbon saturation concept. Global Change Biol. 21, 3200–3209. https://doi.org/10.1111/gcb.12982

Castro, J., Fernández-Ondoño, E., Castro Rodríguez, J., Lallena, A., Sierra, M., Aguilar, J., 2008. Effects of different olive-grove management systems on the organic carbon and nitrogen content of the soil in Jaén (Spain). Soil Till. Res. 98, 56-67. https://doi.org/10.1016/j.still.2007.10.002

Cerdà, A., Lavee, H., Romero-Díaz, A., Hooke, J., Montanarella, L., 2010. Soil erosion and degradation on Mediterranean type ecosystems. Land Degrad. Develop. 21(2), 71–74. https://doi.org/10.1002/ldr.968

Cerdà, A.,2001. Effects of rock fragment cover on soil infiltration, interrill runoff and erosion. Eur. J. Soil Sci. 52, 59–68. https://doi.org/10.1046/j.1365-2389.2001.00354.x

Chabbi, A., Lehmann, J., Ciais, P., Loescher, H.W., Cotrufo, M.F., Don, A.,San Clements, M., Schipper, L.,Six, J., Smith, P., Rumpel, C., 2017. Aligningagriculture and climate policy. Nat. Climate Change 7, 307–309. https://doi.org/10.1038/nclimate3286

Chenu, C., Angers, D.A., Barre, P., Derrien, D., Arrouays, D., Balesdent, J., 2019. Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. Soil Tillage Res. 118, 42–51. https://doi.org/10.1016/j.still.2018.04.011

Colazo, J.C., Buschiazzo, D.E., 2015. The impact of agriculture on soil texture due to wind erosion. Land Degrad. Develop. 26, 62-70. https://doi.org/10.1002/ldr.2297

Dimassi, B., Mary, B., Wylleman, R., Labreuche, J., Couture, D., Piraux, F., Cohan, J.P., 2014. Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. Agric. Ecosyst. Environ. 188, 134–146. https://doi.org/10.1016/j.agee.2014.02.014

Dolan, M.S., Clapp, C.E., Allmaras, R.R., Baker, J.M., Molina, J.A.E., 2006. Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue andnitrogen management. Soil Till. Res. 89, 221–231. https://doi.org/10.1016/j.still.2005.07.015

Du, Z., Ren, T., Hu, C., 2010. Tillage and residue removal effects on soil carbon andnitrogen storage in the North China Plain. Soil Sci. Soc. Am. J. 74, 196–202. https://doi.org/10.2136/sssaj2009.0048

Du, Z., Angers, D.A., Ren, T., Zhang, Q., Li, G., 2017. The effect of no till on organic C storage in Chinese soil should not be over emphasized: a meta analysis. Agr. Ecosys. Environ. 236,1–11. https://doi.org/10.1016/j.agee.2016.11.007

Durán-Zuazo, V.H., Rodríguez Pleguezuelo, C.R., Arroyo Panadero, L., Martínez Raya, A., Francia Martínez, J.R., Cárceles Rodríguez, B., 2009. Soil conservation measures in rainfed olive orchards in south-eastern Spain: impacts of plant strips on soil water dynamics. Pedosphere 19 (4), 453–464.

European Environment Agency. 2019. Climate change adaptation in the agriculture sector in Europe. (https://www.eea.europa.eu/publications/cc-adaptation-agriculture) accessed 20 September 2020.EUROSTAT. 2018. Agriculture, forestry and fishery statistics 2018 edition. Luxembourg: Publications Office of the European Union. ISBN: 978-92-79-94757-5.

FAO, 2006. Guidelines for soil description. Food and Agriculture Organization of the United Nations, Rome. 51–52.

FAO-ISRIC-ISSS. 2015. World reference base for soil resources. A frameworkfor international classification, correlation and communication.World soil resources reports 103. 132 p. Rome

Fernández-Romero, M.L., Lozano-García, B., Parras-Alcántara, L., Collins, C.D., Clark, J.M., 2016. Effects of land management on different forms of soil carbon in olive grovesin Mediterranean areas. Land Degrad. Dev. 27 (4). 1186–1195. http://dx.doi.org/10.1002/ldr.2327

Ferreira, A.O., Amado, T.J., Nicoloso, R.S., Sa, J.C., Fiorin, J.E., Hansel, D.S., Menefee, D., 2013. Soil carbon stratification affected by long-term tillage and cropping systems in southern Brazil. Soil Till. Res. 133, 65–74. https://doi.org/10.1016/j.still.2013.05.011

Ferreira, I.Q., Arrobas, M., Claro, A.M., Rodrigues, M.A., 2013. Soil management in rainfed olive orchards may result in conflicting effects on olive production and soil fertility. Span. J. Agric. Res. 2, 472–480. http://dx.doi.org/10.5424/sjar/2013112-3501

Fleskens L, Stroosnijder L., 2007. Is soil erosion in olive groves as bad as often claimed? Geoderma 141: 260–271. https://doi.org/10.1016/j.geoderma.2007.06.009

Francaviglia, R., Di Bene, C., Farina, R., Salvati, L., Vicente-Vicente, J. L., 2019. Assessing “4 per 1000” soil organic carbon storage rates under Mediterranean climate: a comprehensive data analysis. Mitig. Adapt. Strateg. Glob. Change 24, 795-818. https://doi.org/10.1007/s11027-018-9832-x

Garcia-Franco, N., Albaladejo, J., Almagro, M., Martínez-Mena, M., 2015. Beneficial effects of reduced tillage and green manure on soil aggregation and stabilization of organic carbon in a Mediterranean agroecosystem. Soil Till. Res. 153. 66-75. https://doi.org/10.1016/j.still.2015.05.010

Gál, A. Vyn, T.J.,Michéli, E., Kladivko, E.J., McFee, W.W., 2007. Soil carbon and nitrogen accumulation with long-term no-till versus moldboard plowing overestimated with tilled-zone sampling depths. Soil Till. Res. 96, 42-51. https://doi.otg/10.1016/j.still.2007.02.007

González-Rosado, M., Lozano-García, B., Aguilera-Huertas, J., Parras-Alcántara, L., 2020a. Short-term effects of land management change linked to cover crop on soil organic carbon in Mediterranean olive grove hillsides. Sci. Total Environ. 744, 140683, https://doi.org/10.1016/j.scitotenv.2020.140683

González-Rosado, M., Parras-Alcántara, L., Aguilera-Huertas, J., Benítez, C., Lozano-García, B., 2020b. Effects of land management change on soil aggregates and

organic carbon in Mediterranean olive groves. Catena 195, 104840. https://doi.org/10.1016/j.catena.2020.104840
Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis Global Change Biol. 8, 345-360. https://doi.org/10.1046/j.1354-1013.2002.00486.x
Hernanz, J.L., Sánchez-Girón, V., Navarrete, L., 2009. Soil carbon sequestration and stratification in a cereal/leguminous crop rotationwith three tillage systems in semiarid conditions. Agric. Ecosyst. Environ. 133, 114–122. https://doi.org/10.1016/j.agee.2009.05.009
Hernández, A., Lacasta, C., Pastor, J., 2005. Effects of different management practices on soil conservation and soil water in a rainfed olive orchard. Agric. Water Manage. 77, 232-248. https://doi.org/10.1016/j.agwat.2004.09.030
Hu, S., Li, L., Chen, L., Cheng, L., Yuan, L., Huang, X., Zhang, T., 2019. Estimation of Soil Erosion in the Chaohu Lake Basin through Modified Soil Erodibility Combined with Gravel Content in the RUSLE Model. Water 11 (9), 1806. https://doi.org/10.3390/w11091806
Infante, J., 2011. "Ecología e historia del olivar andaluz. Un estudio socio-ambiental de la especialización olivarera en el sur de España (1750-2000)", tesis doctoral, Universidad Pablo de Olavide de Sevilla.
IPCC (Intergovernmental Panel on Climate Change) 2019. Special report on climate change, desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial ecosystems. Cambridge, UK: Cambridge University press.
IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.
Jarecki, M.K., Lal, R., 2003. Crop management for soil carbon sequestration. Crit. Rev. Plant Sci. 22 (5), 471-502. https://doi.org/10.1080/713608318
Junta de Andalucía 2020. Red de estaciones agroclimáticas de Andalucía. https://www.juntadeandalucia.es/agriculturaypesca/ifapa/ria/servlet/FrontController
Kopittke, P.M., Menzies, N.W., Wang, P., McKenna, B.A., Lombi, E., 2019. Soil and the intensification of agriculture for global food security. Environ. Int. 132, 105078. https://doi.org/10.1016/j.envint.2019.105078
Kundu S., Bhattacharyya R., Prakash V., Ghosh B.N., Gupta H.S., 2007. Carbon sequestration and relationship between carbon addition and storage under rainfed soybean–wheat rotation in a sandy loam soil of the Indian Himalayas. Soil Till. Res. 92 (1-2), 87-95. https://doi.org/10.1016/j.still.2006.01.009
Laghrour, M., Moussadek, R., Mrabet, R., Dahan, R., El-Mourid, M., Zouahri, A., Mekkaoui, M., 2016. Long and mid term effect of conservation agriculture on soil properties in dry areas of Morocco. Appl. Environ. Soil Sci. https://doi.org/10.1155/2016/6345765
Lal, R., 1998. Soil erosion impact on agronomic productivity and environment quality. Crit. Rev. Plant Sci. 17 (4), 319–464. https://doi.org/10.1016/S0735-2689(98)00363-3

Lal, R., 2009. Soil quality impacts of residue removal for bioethanol production. Soil Till. Res. 102, 233–241. https://doi.org/10.1016/j.still.2008.07.003

Lal, R., 2010. Managing Soils and Ecosystems for Mitigating Anthropogenic Carbon Emissions and Advancing Global Food Security. BioScience 60 (9), 708–721. https://doi.org/10.1525/bio.2010.60.9.8

Lal, R., 2018. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. Global Change Biol. 24(8), 1-17. https://doi.org/10.1111/gcb.14054

Lal, R., 2016. Beyond COP 21: Potential and challenges of the "4 per Thousand" initiative. J. Soil Water Conserv. 71 (1), 20A-25A. https://doi.org/10.2489/jswc.71.1.20A

Ledo, A., Smith, P., Zerihun, A., Whitaker, J., Vicente Vicente, J., Qin, Z., Mcnamara, N., Zinn, Y., Llorente, M., Liebig, M., Kuhnert, M., Dondini, M., Don, A., Diaz-Pines, E., Datta, A., Bakka, H., Aguilera, E., Hillier, J., 2020. Changes in soil organic carbon under perennial crops. Global Change Biol. 26 (7). https://doi.org/10.1111/gcb.15120

Liang, X.Q., Wang, Z.B., Zhang, Y.X., Zhu, C.Y., Lin, L.M., Xu, L.X., 2016. No-tillage effects on N and P exports across a rice-planted watershed. Environ. Sci. Pollut. Res. 23, 8598–8609. https://doi.org/10.1007/s11356-016-6112-8

Lionello, P., Scarascia, L., 2018. The relation between climate change in the Mediterranean region and global warming Reg. Environ. Change 18, 1481-1493. https://doi.org/10.1007/s10113-018-1290-1

Liska, A.J., Yang, H., Milner, M., Goddard, S., Blanco-Canqui, H., Letlon, M.P., Fang, X. X., Zhu, H., Suyker, A.E., 2014. Biofuels from crop residue can reduce soil carbon and increase CO_2 emissions. Nat. Clim. Change 4, 398–401. https://doi.org/10.1038/nclimate2187

López, R., Burgos, P., Hermoso, J.M., Hormaza, J.I., González-Fernández, J.J., 2014. Long term changes in soil properties and enzyme activities after almond shell mulching in avocado organic production. Soil Till. Res. 143, 155–163. https://doi.org/10.1016/j.still.2014.06.004

López-Garrido, R., Madejón, E., León-Camacho, M., Girón, I., Moreno, F., Murillo, J.M., 2014. Reduced tillage as an alternative to no-tillage under Mediterranean conditions: A case study. Soil Till. Res. 140, 40–47. https://doi.org/10.1016/J.STILL.2014.02.008

Lou, Y., Xu, M., Chen, X., He, X., Zhao, K., 2012. Stratification of soil organic C, N and C:N ratio as affected by conservation tillage in two maize fields of China. Catena 95, 124-130. https://doi.org/10.1016/j.catena.2012.02.009

MAGRAMA. 2012. Guía Práctica de la Fertilización Racional de los Cultivos en España. 2ª Edicion. Ministerio de Agricultura, Alimentación y Medio Ambiente: Madrid.

MAPA. 2018a. Encuesta sobre superficies y rendimientos de cultivos. Ministerio de Agricultura, Pesca y Alimentación. Madrid. Available in https://www.mapa.gob.es/es/estadistica/temas/estadisticasagrarias/boletin2018_tcm30-504212.pdf

MAPA. 2018b. Encuesta sobre superficies y rendimientos de cultivos. Análisis de las técnicas de mantenimiento del suelo y de los métodos de siembra en España.

Ministerio de Agricultura, Pesca y Alimentación. Madrid. Available in https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/cubiertas2018_tcm30-504664.pdf

Martínez-Mena, M., Garcia-Franco, N., Almagro, M., Ruiz-Navarro, A., Albaladejo, J., de Aguilar, J.M., Gonzalez, D., Querejeta, J.I., 2013. Decreased foliar nitrogen and crop yield in organic rainfed almond trees during transition from reduced tillage to no tillage in a dryland farming system. Eur. J. Agron. 49, 149–157. https://doi.org/10.1016/j.eja.2013.04.006

Mazzoncini, M., Antichi, D., Di Bene, C., Risaliti, R., Petri, M., Bonari. E., 2016. Soil carbon and nitrogen changes after 28 years of no-tillage management under Mediterranean conditions Eur. J. Agron.77, 156-165. https://doi.org/10.1016/j.eja.2016.02.011

Mazzoncini, M., Sapkota, T.B., Bàrberi, P., Antichi, D., Risaliti, R., 2011. Long-term effect of tillage: nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. Soil Till. Res. 2, 165–174. https://doi.org/10.1016/j.still.2011.05.001

Michalzik, B., Kalbitz, K., Park, J.H., Solinger, S., Matzner, E., 2001. Fluxes and concentrations of dissolved organic carbon and nitrogen - a synthesis for temperate forests. Biogeochemistry 52, 173–205. https://doi.org/10.1023/A:1006441620810

Minasny, B., Malone, B. P., McBratney, A. B., Angers, Dominique Arrouays, D. A., Chambers, A., Chaplot, V., Chen, Z. Chengg, K., Das, B. S., Field, D. J., Gimona, A., Hedley, C. B., Young Hong, S., Mandal, B., Marchant, B. P., Martin, M., McConkey, B. G., Mulder, V. L., O'Rourke, S., Richer-de-Forges, A. C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, Ch., Vågen, T. G., van-Wesemael, B., Winowiecki, L., 2017. Soil carbon 4 per mille. Geoderma. 292, 59-86. https://doi.org/10.1016/j.geoderma.2017.01.002

Mohsin Abrar, M., Xu, M.,Atizaz, S., Shah, A., Wajahat Aslam, M., Aziz, T., Mustafa, A., Nadeem Ashraf, M., Zhou, B., Ma, X., 2020. Variations in the profile distribution and protection mechanisms of organic carbon under long-term fertilization in a Chinese Mollisol, Sci. Total Environ. 723, 138181. https://doi.org/10.1016/j.scitotenv.2020.138181.

Morugán-Coronado, A., Linares P.C., Gómez-López, M., Faz, Á., Zornoza, R., 2019. The impact of intercropping, tillage and fertilizer type on soil and crop yield in fruit orchards under Mediterranean conditions: A meta-analysis of field studies. Agr. Syst., 102736. https://doi.org/10.1016/j.agsy.2019.102736

Muñoz-Rojas, M., Doro, L., Ledda, L., Francaviglia, R., 2015. Application of CarboSOIL model to predict the effects of climate change on soil organic carbon stocks in agrosilvo-pastoral Mediterranean management systems. Agr. Ecosyst Environ 202, 8–16. https://doi.org/10.1016/j.agee.2014.12.014

Nieto, OM., Castro, J., Fernández-Ondoño, E., 2013. Conventional tillage versus cover crops in relation to carbon fixation in Mediterranean olive cultivation. Plant Soil 365, 321–335. https://doi.org/10.1007/s11104-012-1395-0

Nieto, O.M., Castro, J., Guzmán, G., Foraster, L. Fernández, E., 2012. Soil management system in the olive orchard and influence on the organic matter and nutrient contents. Acta Hortic. 937, 105-112. https://doi.org/10.17660/ActaHortic.2012.937.12

Oorts, K., Nicolardot, B., Merckx, R., Richard, G., Boizard, H., 2006. C and N mineralization of undisrupted and disrupted soil from different structural zones of conventional tillage and no-tillage systems in northern France. Soil Biol. Biochem. 38, 2576–2586. https://doi.org/10.1016/j.soilbio.2006.03.013

Ordóñez-Fernández, R., González-Fernández, P., Muñoz-Cobo, M. P., 2007. Cubiertas intertes: los restos de poda como protección y mejora de las propiedades del suelo. In Cubiertas Vegetales en Olivar, pp. 159–168. CAP, Junta de Andalucía.

Ouédraogo, E., Mando, A., Stroosnijder, L.,2006. Effects of tillage, organic resources and nitrogen fertiliser on soil carbon dynamics and crop nitrogen uptake in semi-arid West Africa. Soil Till. Res. 91, 57–67. https://doi.org/10.1016/j.still.2005.11.004

Palese AM., Vignozzi N., Celano G., Agnelli AE., Pagliai M., Xiloyannis C., 2014. Influence of soil management on soil physical characteristics and water storage in a mature rainfed olive orchard. Soil Till. Res 144, 96–109. https://doi.org/10.1016/j.still.2014.07.010

Palese, A.M., Ringersma, J., Baartman, J.E.M., Peters, P., Xiloyannis, C., 2015. Runoff and sediment yield of tilled and spontaneous grass-covered olive groves grown on sloping land. Soil Res. 53, 542–552. https://doi.org/10.1071/SR14350

Palma, R.M., Saubidet, M.I., Rimolo, M., Utsumi, J., 1998. Nitrogen losses by volatilization in a corn crop with two tillage systems in the Argentine Pampa Commun. SoilSci. Plant Anal. 29, 2865-2879. https://doi.org/10.1080/00103629809370161

Parras-Alcántara L., Martín-Carrillo M., Lozano-García B., 2013. Impacts ofland use change in soil carbon and nitrogen in a Mediterraneanagricultural area (Southern Spain). Solid Earth 4, 167–177. https://doi.org/10.5194/se-4-167-2013

Parras-Alcántara, L., Lozano-García, B., 2014. Conventional tillage versus organic farming in relation to soil organic carbon stock in olive groves in Mediterranean rangelands (southern Spain). Solid Earth 5, 299-311. https://doi.org/10.5194/se-5-299-2014

Pastor, M., 2004. Sistemas de manejo del suelo. En: Barranco, D., Fernández-Escobar, R., Rallo, L. (Eds). El Cultivo del Olivo. Ed. Consejería de Agricultura Junta de Andalucía – Mundi Prensa S.A. 229-285.

Plante, A.F., Conant, R.T., Stewart, C.E., Paustian, K., Six, J., 2006. Impact of soil texture on the distribution of soil organic matter in physical and chemical fractions. Soil Sci. Soc. Am. J. 70, 287–296. https://doi.org/10.2136/sssaj2004.0363

Poesen, J., De Luna, E., Franca, A., Nachtergaele, J., Govers, G., 1999.Concentrated flow erosion rates as affected by rock fragment cover and initial soil moisture content. Catena, 36, 315–329. https://doi.org/10.1016/S0341-8162(99)00044-2

Porta, J.; López-Acevedo, M.; Roquero, C., (eds.) 2003. Edafología para la agricultura y el medio ambiente. 3ª ed. Mundi-Prensa, Madrid, 929 p

Poulton, P., Johnston, J., Macdonald, A., White, R., Powlson, D., 2017. Major limitationsto achieving “4 per 1000” increases in soil organic carbon stock in temperateregions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. Glob Change Biol. 24(6), 2563-2584. https://doi.org/10.1111/gcb.14066

Powlson, D.S., Whitmore, A.P., Goulding, W.T., 2011. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. Eur. J. Soil Sci. 62, 42–55. https://doi.org/10.1111/j.1365-2389.2010.01342.x

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Change 4, 678–683. https://doi.org/10.1038/nclimate2292

Pu, C., Kan, Z.R., Liu, P., Ma, S.T., Qi, J.Y., Zhao, X., Zhang, H.L.,2019. Residue management induced changes in soil organic carbon and total nitrogen under different tillage practices in the North China Plain. J. Integr. Agric. 18, 1337-1347. https://doi.org/10.1016/S2095-3119(18)62079-9

Puget, P., Lal, R., 2005. Soil organic carbon and nitrogen in a Mollisol in central Ohio as affected by tillage and land use. Soil Till. Res. 80, 201-213. https://dx.doi.org/10.1016/j.still.2004.03.018

Pulleman, M.M., Six, J., van Breemen, N., Jongman, A.G., 2005. Soil organic matter distribution and microaggregate characteristic as affected by agricultural management and earthworm activity. Eur. J. Soil Sci. 56, 453–467. https://doi.org/10.1111/j.1365-2389.2004.00696.x

Ramos, M.E., Benítez, E., García, P.A., Robles, A.B., 2010. Covercrops under different managements vs. frequent tillage inalmond orchards in semiarid conditions: Effects on soilquality. Appl. Soil Ecol. 44, 6-14. https://doi.org/10.1016/j.apsoil.2009.08.005

Rezaei, S.A., Gilkes, R.J., 2005. The effects of landscape attributes and plant community on soil chemical properties in Rangelands. Geoderma 125, 167–176. https://doi.org/10.1016/j.geoderma.2004.07.010

Rodrigo-Comino, J., García-Díaz, A., Brevik, E.C., Keestra, S.D., Pereira, P., Novara, A., Jordán, A., Cerdà, A.,2017. Role of rock fragment cover on runoff generation and sediment yield in tilled vineyards. Eur. J. SoilSci. 68, 864–872. https://doi.org/10.1111/ejss.12483

Rumpel, C., Amiraslani, F., Chenu, C., Garcia Cardenas, M., Kaonga, M., Koutika, L.-S., Ladha, J., Madari, B., Shirato, Y., Smith, P., Soudi, B., Soussana, J.F., Whitehead, D., Wollenberg, E., 2019. The 4p1000 initiative: opportunities, limitations andchallenges for implementing soil organic carbon sequestration as a sustainable development strategy. AMBIO 49, 350–360. https://doi.org/10.1007/s13280-019-01165-2

Sastre, B., Marques, M.J., García-Díaz, A., Bienes, R., 2018. Three years of management with cover crops protecting sloping olive groves soils, carbon and water effects on gypsiferous soil. Catena 171, 115-124. https://doi.org/10.1016/j.catena.2018.07.003

Sastre, B., Barbero-Sierra, C., Bienes, R., Marques, M.J., García-Díaz, A.,2017. Soil loss in an olive grove in Central Spain under cover crops and tillage treatments, and farmer perceptions. J. Soils Sediments 17, 873–888. https://doi.org/10.1007/s11368-016-1589-9

Tolk, J.A., 2003. Soils. permanent wilting points. Encycl. Water Sci. http://dx.doi.org/10.1081/E-EWS

Torrent, J., 2005. Mediterranean soils. In: Hillel, D. (Ed.), Encyclopedia of Soils in the Environment. Academic Press, London, pp. 418–427.

UNFCC (United Nations Framework Convention on Climate Change). 2015. COP21 Climate Agreement. Paris, France: United Nations Framework Convention on Climate Change.

Ussiri, D.A.N, Lal, R., 2009. Long-term tillage effects on soil carbon storageand carbon dioxide emissions in continuous corn cropping system from an Alfisol in Ohio. Soil Tillage Res. 104, 39–47. https://doi.org/10.1016/j.still.2008.11.008

Varvel, G.E., Wilhem, W.W., 2011. No-tillage increases soil profile carbon and nitrogen Ander long-term rainfed cropping system. Soil Till. Res. 114, 28-36. https://doi.org/10.1016/j.still.2011.03.005

Vazquez, E., Benito, M., Espejo, R., Teutscherova, N.,2019. Effects of no-tillage and liming amendment combination on soil carbon and nitrogen mineralization. Eu. J. Soil Biol. 93,103090. https://doi.org/10.1016/j.ejsobi.2019.103090

Verheye, W., De la Rosa, D., 2005. Mediterranean soils. In land use and land cover, from Encyclopedia of life support systems (EOLSS), Developed under the Auspices of the UNESCO, EOLSS Publishers: Oxford, UK. http://www.eolss.net

Vicente-Vicente, J.L., García-Ruiz, R., Francaviglia, R., Aguilera, E., Smith, P., 2016. Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta analysis. Agric. Ecosyst. Environ. 235, 204 214. https://doi.org/10.1016/j.agee.2016.10.024

Vicente-Vicente, J.L., Gómez-Muñoz, B., Hinojosa-Centeno, MB., Smith, P., Garcia-Ruiz, R., 2017.Carbon saturation and assessment of soil organic carbon fractions in Mediterranean rainfed olive orchards under plant cover management. Agric. Ecosyst. Environ. 245, 135–146. https://doi.org/10.1016/j.agee.2017.05.020

Virto, I., Imaz, M., Enrique, A., Hoogmoed, W., Bescansa, P., 2007. Burning crop residues under no-till in semi-arid land, Northern Spain—effects on soil organic matter, aggregation, and earthworm populations. Aust. J. Soil Res. 45, 414–421. https://doi.org/10.1071/SR07021

Wang, W.J., Dalal, R.C., 2006. Carbon inventory for a cereal cropping system undercontrasting tillage. Nitrogen fertilisation and stubble management practices. Soil Till. Res. 91, 68–74. https://doi.org/10.1016/j.still.2005.11.005

Wiesmeier, M., Mayer, S., Burmeister, J., Hübner, R., Kögel-Knabner, I., 2020. Feasibility of the 4 per 1000 initiative in Bavaria: A reality check of agricultural soil management and carbon sequestration scenarios. Geoderma. 369. https://doi.org/10.1016/j.geoderma.2020.114333

Yamashita, T., Feiner, H., Bettina, J., Helfrich, M., Ludwig, B., 2006. Organic matter in density fractions of water-stable aggregates in silty soils: effect of land use. Soil Biol. Biochem. 38, 3222–3234. https://doi.org/10.1016/j.soilbio.2006.04.013

Yang, X.M., Drury, C.F., Reynolds, W.D., Tan, C.S., 2008. Impacts of long-term and recentlyimposed tillage practices on the vertical distribution of soil organic carbon. Soil Till. Res. 100, 120-124. https://doi.org/10.1016/j.still.2008.05.003

Yazdanpanah N., Mahmoodabadi M., Cerdà A., 2016. The impact of organic amendments on soil hydrology, structure and microbial respiration in semiarid lands. Geoderma, 266: 58–65. https://doi.org/10.1016/j.geoderma.2015.11.032

Zajícová, K., Chuman, T., 2019. Effect of land use on soil chemical properties after 190 years of forest to agricultural land conversion. Soil Water Res. https://doi.org/10.17221/5/2018-SWR

Zhang, P., Wei, T., Li, YL., Wang, K., Jia, ZK., Han, QF., Ren X L., 2015. Effects of straw incorporation on the stratification of the soil organic C, total N and C:N ratio in a semiarid region of China. Soil Till. Res. 153, 28–35. https://doi.org/10.1016/j.still.2015.04.008

Zuber, S.M., Behnke, G., Nafziger, E.D., Villamil, M.B., 2015. Crop rotation and tillage effects on soil physical and chemical properties in Illinois. Agron. J. 107, 971–978. https://doi.org/10.2134/agronj14.0465

Effects of land management change on soil aggregates and organic carbon in Mediterranean olive groves

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Effects of land management change on soil aggregates and organic carbon in Mediterranean olive groves

Manuel González-Rosado[a], Luis Parras-Alcántara[a], Jesús Aguilera-Huertas[a], Concepción Benítez[b], Beatriz Lozano-García[a,*]

[a] SUMAS Research Group, Department of Agricultural Chemistry, Soil Science and Microbiology, Faculty of Science, Agrifood Campus of International Excellence - ceiA3, University of Córdoba, 14071 Córdoba, Spain
[b] Química Agrícola y Edafología Research Group, Department of Agricultural Chemistry, Soil Science and Microbiology, Faculty of Science, Agrifood Campus of International Excellence - ceiA3, University of Córdoba, 14071 Córdoba, Spain

ARTICLE INFO

Keywords:
Conventional tillage
No tillage
Mediterranean environment
Soil depth
Aggregate stability
Aggregate-associated C

ABSTRACT

4.2.1. Introduction.

One of the strategies to fight against the climate change is to promote soil carbon sequestration in soils, due to soils can act as carbon sink (Brevik *et al*., 2015). In fact, after the United Nations Framework Convention for Climate Change: Conference of the Parties (UNFCCC COP 21) in Paris, this strategy focused the attention not only on forest soils but also on agricultural lands (Zomer *et al*., 2017).

Scientific worldwide have demonstrated that soil organic carbon (SOC) sequestration is a win–win strategy because soil becomes in a carbon sink decelerating the observed climate change and the increase in the amount of SOC improves physical, chemical and biological soil properties (Cotrufo *et al*., 2019). However, there are lots of agricultural practices and uses affecting soil properties, aggravating soil degradation processes and accelerating soil erosion. One of them is the conventional tillage (CT). CT implies intense tillage, destruction of soil macroaggregates and the acceleration of organic matter decomposition by higher exposition to microorganisms and stimulation of the organic matter oxidation processes (Six *et al*., 2000a; Abid and Lal, 2008).

On the contrary, conservation tillage helps to improve soil properties. Conservation agriculture includes a wide range of agricultural practices among others conservation tillage (i.e. no tillage), permanent soil coverage and diversification of crop species (FAO, 2020). In Mediterranean agroecosystems, conservation agriculture is recognized as the best agricultural management system to reduce soil erosion rates and maintain adequate SOC content levels (Lee *et al*., 2019). Conservation agriculture techniques increase soil fertility and stability in addition to biological activity due to the maintained inputs of soil organic matter (Fernández-Romero *et al*., 2016a; Fernández-Romero *et al*., 2016b; Morugán-Coronado *et al*., 2020).

Woody crops soils in Mediterranean areas have a high potential to provide many ecosystem services, such as food production, carbon sink, biodiversity or climate change mitigation (Aguilera *et al*., 2013; Lee *et al*., 2019). The capacity of the soil to provide these functions will be determined by the management practices implemented on the farm. Therefore, soil management can affect the relative balance of these processes and their environmental impacts. In addition, unsustainable practices such as intensive tillage are detrimental to the provision of these ecosystem services within the Mediterranean agroecosystems (Francaviglia *et al*., 2018).

Olive grove soils are generally characterized by low level of organic matter, which influences their structure, stability and quality (Castro *et al*., 2008; Milgroom *et al*., 2007; Lozano-García and Parras-Alcántara, 2014), sometimes presenting problems of crusting. These processes and the lack of appropriate levels of organic matter increase surface runoff and reduce infiltration by encouraging erosive processes and reducing water storage in the soil (Franzluebbers, 2002). Among the major identified causes of degradation and erosion processes we can find the presence of sloping soils, intense use of tillage, low coverage of soils, irregular and often torrential rainfall typical to the pluviometric regime in the Mediterranean climate (Pastor, 2004). The combination of these factors impoverishes soils dedicated to olive-growing, affects their structure, increases their degradation and therefore reduces their quality and productive capacity (Sastre *et al*., 2018; Brilli *et al*., 2019). In the last decades, farmers have been treating to solve these problems. Farmers were concerned about the reduction in profitability of the olive grove due to decreased productivity and low prices. Therefore, in the last decade, CT has been changed by no tillage with bare soil and the application of pre-emergence herbicide in a huge amount of olive groves in the south of Spain.

The strong relationship between aggregate stability and organic carbon (OC) has been widely documented (Six *et al*., 2004; Tisdall and Oades, 1982; Chenu *et al*., 2000; Zheng *et al*., 2018), even suggesting the deterioration of macroaggregates as the primary mechanism causing soil carbon loss (Six *et al*., 1998; Six *et al*., 1999; Xie *et al*., 2015). Consequently, since soil aggregates and organic matter content maintain an important correlation, elevated index of stability of soil aggregates can be an important factor for carbon sequestration and an interesting tool for mitigating global warming (Almaraz *et al*., 2009).

Soil biology plays a crucial role in the mechanism of aggregate stabilization (Zhang *et al*., 2012), bacteria and fungi generally appear as important factors for soil aggregation, especially strongly affecting macroaggregation (Lehmann *et al*., 2017) particularly in conservation tillage systems where a maintenance of soil biodiversity is promoted.

It is therefore necessary to analyze the SOC and to determine factors that can lead to a reduction or an increase in the percentage of organic matter, since these alterations will have a direct influence on the structural stability of the soil (Li *et al*., 2016). Also, it is interesting to determine its relationship deeper in the soil profile, under different mineralogical conditions and where the land management has less impact (Fernández-Romero *et al*., 2016a; Fernández-Romero *et al*., 2016b). The depth of sampling is an important factor to evaluate the soil stability and SOC, several studies have demonstrated the importance of the subsoil as a CO_2 sink (Salomé *et al*., 2010; Zhang *et al*., 2016; Zhao *et al*., 2014; Lozano-García *et al*., 2017).

In this study, a non-experimental olive grove was selected to determine the long-term effects of NT + bare soil (NT+H) on aggregate stability and SOC associated with aggregate-size fractions. Our objective was to demonstrate if NT + bare soil is as beneficial in olive grove as farmers would expect, determining changes on soil aggregates and SOC both in soil surface (A horizon) and in depth (Bw, BC and C horizons) after management change from CT to NT+H in the olive grove to check if soil aggregates and SOC associated were different between managements in depth too.

4.2.2. Materials and methods.

4.2.2.1. Study area.

A field study was conducted on a slope facing southwest with an average gradient of about 6%, located within an olive grove (*Olea europaea* var. *picual*) with unirrigated conventional permanent monocropping system (12 m × 12 m pattern) in Torredelcampo – Jaen (Andalusia, Spain, 37°46′26.0″N, 3°54′41.5″W) (Figure 1). The representative soils were Calcaric Cambisols according to IUSS Working Group WRB (FAO, 2015). Climate is defined by an important seasonal thermal contrast, the annual average precipitation was 493.2 mm, and monthly rainfall ranges from 2.1 mm (July) to 75 mm (December) - all data for the period 1983–2010 (AEMET, 2020).

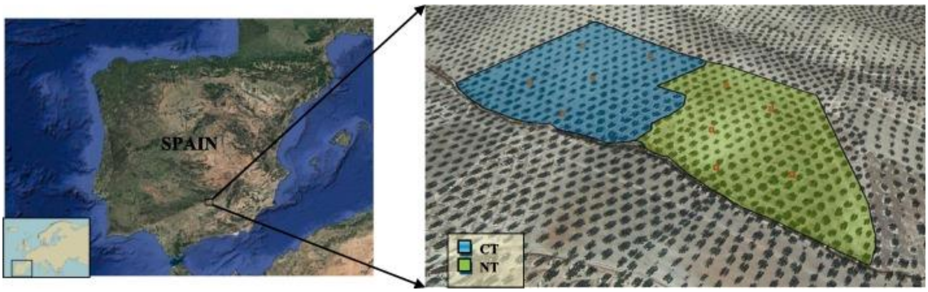


Figure. 1. Study area. Orange circles represent soil sampling points.

4.2.2.2. Experimental design and soil sampling.

Two sites of different tillage practices were selected for the study: (i) conventional tillage (CT) managed with disk harrow (an annual pass) and cultivator in spring followed by a tine harrow in summer to control weeds; pruning residues each two years (6 Mg ha^{-1}); use of fungicides (Copper oxychloride 34.5% w.p.); herbicides (a broad-spectrum herbicide is added in autumn to control weeds under trees to allow the harvest of the olives); and mineral fertilizer (100 kg urea ha^{-1}, 46%N) is applied in alternate years during winter, just after the harvest and (ii) no-till with bare soil (NT+H) without any mechanical practice but with the same application of pruning residues, fungicides, fertilizers and the application of pre-emergenge herbicide in winter and spring to control weeds in the case of abundant rain. Both plots were of 3 ha with 200 olive trees. The CT plot has been under this manage about for 80 years and NT+H plot, 15 years.

These plots were no replicated because it was not an experimental farm, it was a real farm. Therefore, plots were divided in 5 sub-plots. Soil was sampled in the 5 sub-plots considered as pseudo-replicates. Soil samples (1 soil profiles × 5 subplots × 2 managements = 10 complete soil profiles by horizons) were taken in September2019 after the harvest. Pruning residues are applied in February in alternate years but they were applied in 2017.

4.2.2.3. Analytical determinations.

40 samples were taken from the field (10 profiles × 4 horizons each one), stored in plastic bags and, once in the laboratory, air dried and passed through a 2 mm sieve to separate fine earth to skeleton and to remove roots, plant litter material. At the same time, one soil core was taken per plot and soil horizon to determinate bulk density by the core method (Blake and Hartge, 1986).

Three replicates of each sample were determined in laboratory; therefore, values are the mean of three replicates ± SD.

Soil particle size distribution was analyzed by the Bouyoucos hydrometer method. Before determining the particle size distribution, samples were treated with H_2O_2 (6%) to remove organic matter. SOC was calculated using the Walkley and Black method (Nelson and Sommers, 1982) and the carbonate content, by using a Bernard calcimeter (Álvaro-Fuentes *et al*., 2019).

For aggregate analysis the wet sieving procedure by Elliott (1986) was used (Álvaro-Fuentes *et al*., 2019). Briefly, 100 g soil air-dried (8 mm sieved) was separated to obtain four aggregate size fractions by wet sieving using sieves of 2.0, 0.25 and 0.053 mm diameter. Soil samples were placed on the top of a 2 mm sieve and subsurmerged for 5 min in deionized water at room temperature. After slaking the sieving was done manually, 50 times was moved up and down in 2 min to achieve aggregate separation. Soil particles retained on each sieve were collected and dried at 50 °C into the oven, once dry they were weighed and SOC was determined in each one using the Walkley and Black method (Nelson and Sommers, 1982).

The mean weight diameter (MWD) were calculated by Kemper and Rosenau method (1986):

$$MWD = \sum_{i=1}^{4} x_i w_i$$

where x_i is the mean diameter of size class (large macroaggregates > 2; small macroaggregates 2–0.25 mm; microaggregates 0.25–0.053 mm; silt and clay < 0.053 mm) and w_i is the proportion of the total sample mass in the corresponding size fraction after deducting the mass of stones (upon dispersion and passing through the same sieve) as indicated above.

SOC was calculated in each size fraction using the Walkley and Black method (Nelson and Sommers, 1982) such as in the total sample.

The SOC stock (SOC-S) was calculated as follows (Eynard *et al*., 2005):

$$SOC - S = Bd\ H\ (1 - \delta) \sum_{i=1}^{4} m_i SOC_i$$

where Bd is the bulk density of the soil sample, H is the soil horizon thickness, δ is the mass fraction of gravel (%) in the soil sample, SOC_i is the soil organic carbon content in ith size aggregate (g kg^{-1}), m_i is the ith size aggregate content (%).

The effect of land management and depth on soil properties was analyzed using ANOVA (SPSS 13.0 for Windows). Data were tested for normality to verify the model assumptions, and differences of $p < 0.05$ were considered statistically significant.

4.2.3. Results.

4.2.3.1. Soil aggregates-size distribution and mean weight diameter of aggregates

Soil water stable aggregate size distribution in each soil horizon is shown in Figure 2. Aggregate size distribution in the surface horizon was affected by showing the lowest values in terms of total stable macroaggregates (>0.25 mm). In both treatments this fraction was about 30% of the total stable aggregates (32.7% in CT and 24.9% in NT+H) (Figure 2a). In this sense, in this horizon appeared the highest proportions of microaggregates (0.25–0.053 mm), being significantly ($P < 0.05$) higher in NT+H than in CT. This size fraction was the dominant in all cases, independent of the treatment or depth (except in Bw-CT). But in the surface horizon, it reached values around 50%. Only in the surface horizon the proportion of microaggregates had larger contribution than macroaggregates (large macroaggregates + small macroaggregates) in both treatments (67.2% in CT and 75.1% in NT+H). Related to the macroaggregates, in the A horizon, CT had higher total macroaggregates values (large macroaggregates + small macroaggregates), however NT+H had more percentage of large macroaggregates (>2 mm) (15.8% *vs.* 6.7%).

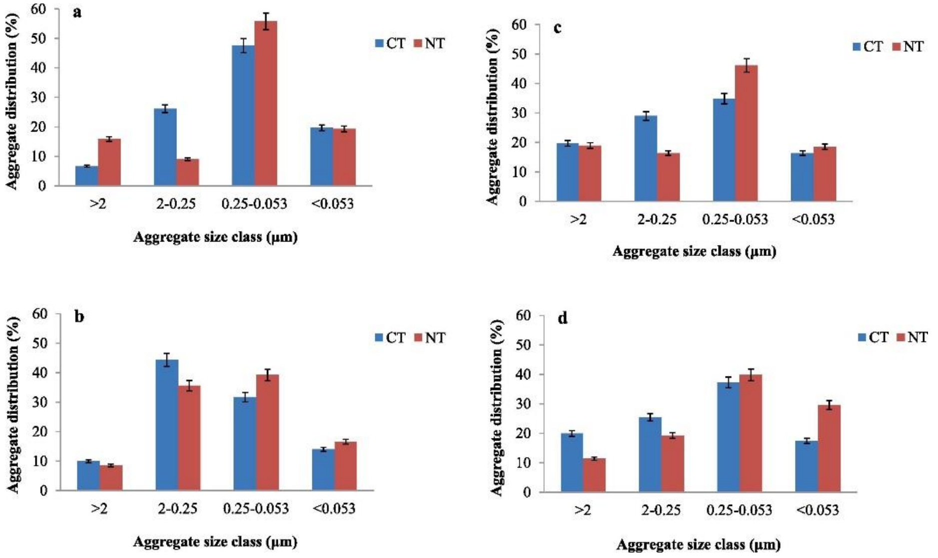


Figure 2. Water stable aggregate size distribution in different soil horizons as influenced by tillage treatments. a: A horizon; b: Bw horizon; c: BC horizon; d: C horizon; CT: conventional tillage; NT: no-till with bare soil. Error bars represent standard error.

In both treatments the same trend in total macroaggregates was detected in the subsurface horizons (from Bw to C), this size fraction decreased in depth, whereas in CT the microaggregates increased and in NT+H the microaggregates did not change in depth, being the silt and clay fraction which suffered the increase in depth. In both managements, B horizon was the horizon with the highest proportion of macroaggregates (>0.25 mm) (54.3% in CT and 44.2% in NT+H) (Figure 2b).

The MWD was greater with the absence of tillage only in the surface horizon (0.76 mm in A-NT+H and 0.61 mm in Ap-CT) (Figure 3). On the contrary, in the subsurface horizons, CT obtained the highest values in MWD. In general, the MWD values (Figure 3) increased with depth in both treatments except in the C horizon for NT+H.

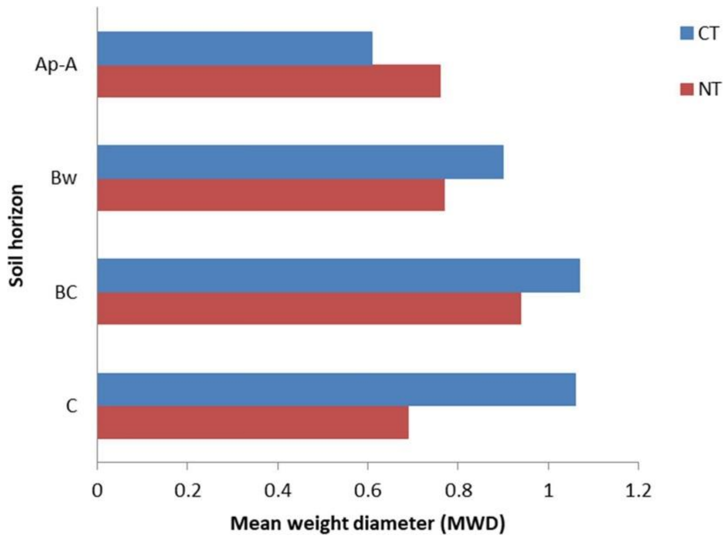


Figure 3. Mean weight diameter (MWD) of aggregate size fractions in different soil horizons as influenced by tillage treatments. CT: Conventional tillage; NT: No till.

4.2.3.2. OC associated with aggregate-size fractions.

Data on the OC concentrations (g kg^{-1}) in the different aggregate size classes are reported in Figure 4. The OC contents in soil aggregates in both treatments displayed a decreasing trend from topsoil to deep soil.

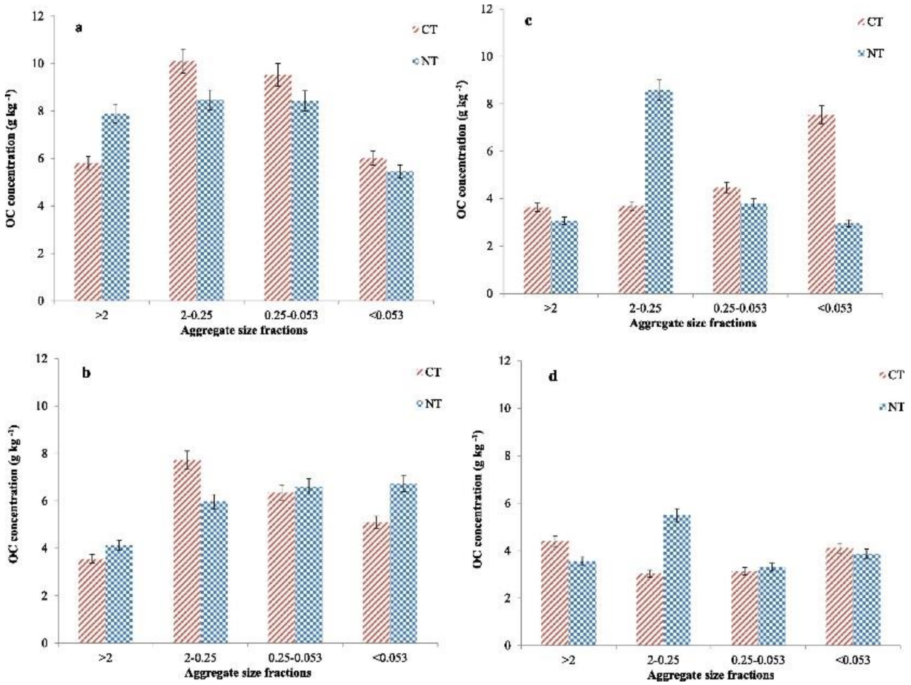


Figure 4. OC (organic carbon) concentrations in aggregate size fractions. a: A horizon; b: Bw horizon; c: BC horizon; d: C horizon; CT: conventional tillage; NT: no-till with bare soil. Error bars represent standard error.

Within the macroaggregate fraction the highest OC values were found in the small macroaggregates (2–0.25 mm) in all horizons analyzed except in the C horizon under CT where large macroaggregates obtained the highest values.

The highest OC concentrations in the study area were found in the A horizon (Figure 4a). In this horizon, both treatments had the largest OC concentrations in the macroaggregates fraction with around 50% of OC, while silt + clay was the lowest concentration, about 20%. In this surface horizon, NT+H contained 34% more OC contents in large macroaggregates over CT, however in the total macroaggregates fraction there were no significant ($P < 0.05$) differences between both managements. In this horizon, OC content in CT was slightly higher (4%) than in NT+H treatment. The OC concentrations remained homogeneous between the fractions in NT+H while in CT there were more differences in the concentrations between the different size fractions.

The trend in depth was, in general, slightly higher OC associated with aggregate-size fractions under CT than in NT+H, although there were not significant ($P < 0.05$) differences (Figure 4b, c, d).

4.2.3.3. Soil organic carbon stock within aggregate fractions.

In general, as shown in Figure 5, in both treatments the water stable microaggregates had larger contribution to C stock than the C stored in the other fractions and represented 52.5% and 71.6% of the total C stock under CT and NT+H profiles respectively (Figure 6), with the exception of the Bw horizon under CT. In this horizon the C stock in microaggregates was not the highest, due to the C stored in small macroaggregates was 62.2% (Figure 6). C stock in microaggregate fraction considering the complete soil profile was on average 10.3% greater under NT+H than in CT (16.0 Mg ha^{-1} *vs.* 13.1 Mg ha^{-1}) (Figure 5). The major variation in the microaggregate C stock between NT+H and CT was observed in the Bw horizon (6.3 *vs.* 2.3 Mg ha^{-1}) (Figure 5).

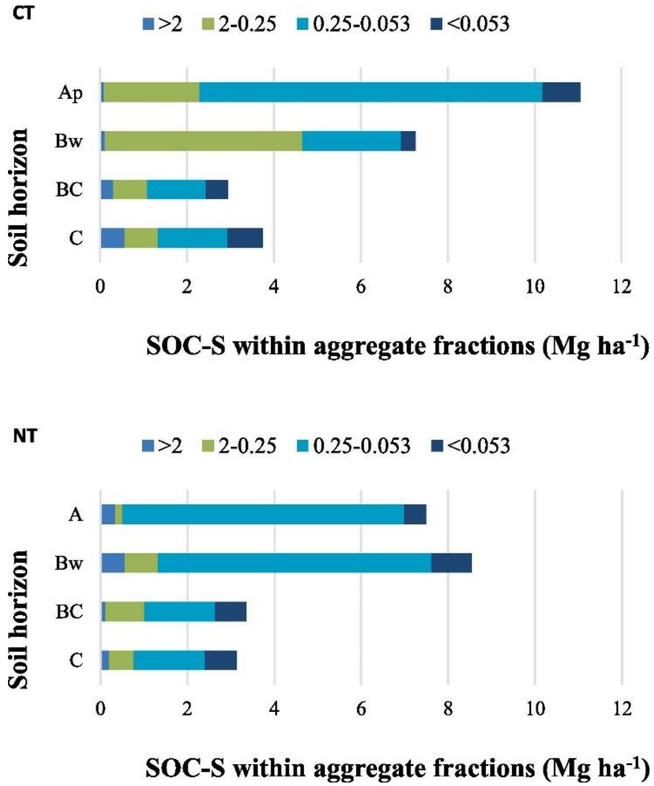


Figure 5. Distribution of SOC-S within aggregate fractions as affected by tillage system, in different horizons soil horizons. CT: Conventional tillage; NT: No tillage.

The water-stable macroaggregates C stock taking into account the complete soil profile was significantly (*P < 0.05*) higher under CT tillage than under NT+H (9.4 *vs.* 3.6 Mg ha^{-1}) (Figure 5). Being the main differences in the small macroaggregates (8.3 Mg ha^{-1} in CT and 2.4 Mg ha^{-1} in NT+H), whereas in the C stored in large macroaggregates there was not any difference (*P < 0.05*). This fraction (>2mm) contributed with the lowest percentages to the total C Stock in both managements (4.3% in CT and 5.3% in NT+H) (Figure 6). In surface horizon + Bw horizon, NT+H had more C stock in large macroaggregates (4.5% in A and 6.5% in Bw) but less in small macroaggregates (2.2% in A and 8.9%) than CT (large macroaggregates: 0.8% in A and 1.5% in Bw; small macroaggregates: 19.8% in a and 62.6% in Bw) (Figure 6). Whereas, in depth (BC and C horizons) the C stock in small macroaggregates was similar in two managements and C stock in large macroaggregates was around three times higher under CT.

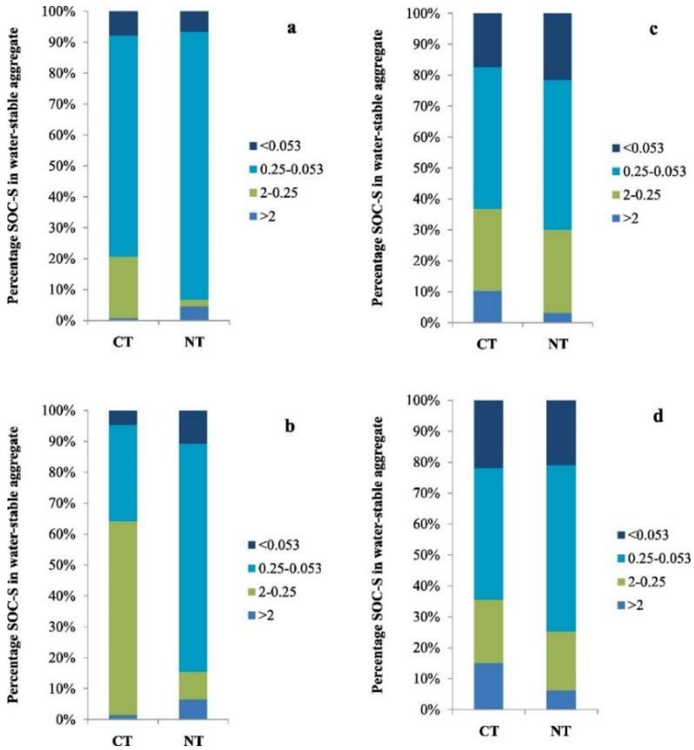


Figure 6. Percentage of SOC-S in water-stable aggregate fractions in different horizons. a: A horizon; b: Bw horizon; c: BC horizon; d: C horizon; CT: conventional tillage; NT: no-till with bare soil.

In general, Figure 5, Figure 6 show that silt + clay was which the least C stored under two managements and considering all horizons. The percentage of C stock in silt + clay fraction (<53 µm) followed a trend to increase in depth in both treatments. Therefore, in this size fraction the highest values were obtained in the deepest horizons (BC and C) achieved around of 20% of total C stock in aggregates in each horizon. No differences ($P < 0.05$) were observed between managements in C stocks in silt + clay.

4.2.4. Discussion.

4.2.4.1. Changes in aggregation distribution in soil profile

We observed that in the surface horizon, microaggregates dominated with independence of the treatments, 47.6% in CT and 55.8% in NT+H (Figure 2). These results can be attributed to mechanized tillage and no tillage without coverage managements (Lal, 2004; Pinheiro *et al*., 2004). Dominance of the microaggregates fraction in the surface soil layer implies the exclusion of porous spaces (Six *et al*., 2004) due to the higher density and internal hardness (Boix-Fayos *et al*., 2001). This fact can have significant repercussions on crusting and aggravated soil degradation through accelerating erosion (Nath and Lal, 2017). Furthermore, in Andalusia's olive groves water erosion is the main cause of soil degradation. High rates of erosion appear in these areas, with estimates well above the tolerable value of 1 t ha^{-1} year^{-1} (MITECO, 2017). However, this value too conservative and high rates of erosion appear in these areas, with estimates well above the value of 10 t ha^{-1} year^{-1} (De la Rosa *et al*., 2005; Francia *et al*., 2006).

The clay content showed high values in the studied soils, above 58% (Table 1). Clay content of the soil is a crucial factor in soil aggregation, however, according with Wagner et al. (2007) further aggregation only occurred in clayey soils with large organic amendment rates and soil organic matter is clearly an important factor in the longevity of newly formed soil aggregates. Therefore, clay content has an important influence on microaggregates although for the macroaggregates formation and stabilization the increase of organic matter percentages is a determinant feature (Boix-Fayos *et al*., 2001).

Tillage regimes apparently influenced soil aggregation distribution in the upper layer (Figure 2a). In this layer, the NT+H system improved the formation level of the >2 mm aggregate (15.8%) while CT system produced mechanical disruption on soil aggregates reducing the amount of large macroaggregate fraction (6.7%). However, in the total macro-aggregates (large + small macroaggregates) CT had large contribution than NT+H, indicating that the positive no tillage effect was much more evident in the larger macroaggregates > 2 mm size than in the smaller macroaggregate-size classes. Therefore, according to these values, together with the results obtained in other studies, large macroaggregates were more vulnerable to breakdown by tillage practice (Ashagrie *et al*., 2007; Zhang *et al*., 2012).

Tillage practice	Hor.	Depth cm	Gravel %	Sand %	Silt %	Clay %	BD Mg m^{-3}	$CaCO_3$ %	A-SOC-STOCK Mg ha^{-1}
	Ap	0-32.7	15.6±3.6Aa	9.2±5.2 Aa	19.1±5.0Aa	71.6±2.8Aa	1.3±0.14 Aa	32.1±2.5 Aa	11.0±1.6 Aa
CT	Bw	32.7-65	15.8±5.1 Aa	3.6±4.4 Ba	21.0±2.0Aa	75.3±7.0Aa	1.3±0.07 Aa	32.0 ±3.7 Aa	7.26±1.1 Ba
	BC	65-89.7	21.7±2.2 Ba	6.5±3.6Ca	20.6±4.8Aa	72.9±2.8Aa	1.4±0.09 Aa	30.6±1.9 Aa	2.9±0.8 Ca
	C	89.7-119.7	12.2±0.3Aa	9.7±0.5Aa	21.5±0.1Ab	68.7±2.2Ab	1.4±0.04 Aa	29.8±2.8 Ab	3.7±1.0 Ca
	A	0-21.7	15.0±2.5 Ab	9.8±2.1 Aa	26.7±5.9Ab	63.5±4.8Ab	1.4±0.07 Aa	29.4±3.1 Aa	7.5±2.3 Ab
NT	Bw	21.7-60	17.6±2.1 Aa	12.9±5.6 Bb	25.9±4.9 Aa	61.2±6.2Ab	1.4±0.03 Aa	37.6±4.6 Bb	8.5±1.9 Aa
	BC	60-84.7	21.5±1.2 Bb	12.3±9.6Bb	29.1±5.5 Ab	58.6±7.9Ab	1.4±0.04 Aa	30.3±3.6 Aa	3.3±0.9 Ba
	C	84.7-110	12.7±0.8 Aa	6.9±0.72Cb	24.8±3.4 Ab	68.2±7.6Aa	1.4±0.03 Aa	30.9±2.7 Ab	3.0±1.2 Ba

Table 1. Basic soil physical and chemical properties in Cambisol olive grove. Data are means ± SD.
CT: conventional tillage; NT: no tillage; Hor: Horizon type; BD: Bulk density; A-SOC-STOCK: Aggregates soil organic carbon stock;
Numbers followed by different capital letters within the same column have significant differences ($P<0.05$) between depths considering the same land use.
Numbers followed by different lower case letters within the same column have significant differences ($P < 0.05$) between the same soil sections in different land use considering the same variable.

It is well established that soils with higher levels of stable aggregates and higher MWD have a stronger resistance to soil degradation and erosion (Celik, 2005). Our data showed, in both treatments, that the MWD of soil aggregates increased with soil depth (Figure 3). In agricultural soils, greater MWD values in subsoil than in topsoil has been reported widely (Du *et al*., 2013; Shu *et al*., 2015; Kalhoro *et al*., 2017) although other studies showed the opposite trend (Abid and Lal, 2008; Wang *et al*., 2019). Higher MWD values in subsoil imply a larger structural stability on deeper horizons, due to larger MWD means that a greater percentage of macroaggregates are retained on the sieves with superior meshes. This trend towards a higher proportion of macroaggregates in depth could have a positive effect in water retention because greater size aggregates contain a higher porosity and thus have a higher capacity to store water for longer periods of time (Briedis *et al*., 2012). This is particularly interesting in the study area and in regions with Mediterranean climatic conditions where irregular precipitation and long periods of water stress are one of the main limitations in crop establishment and productivity (Morugán-Coronado *et al*., 2020).

Our results showed a slight difference in the MWD values of water-stable aggregates in the surface horizon between the managements studied, being the highest values observed for NT+H treatment. In Mediterranean Spain, the reduction of tillage intensity has been shown as a good alternative to increase the aggregate stability in the soil surface (Álvaro-Fuentes *et al*., 2009). Other studies focused on different crops located in the Mediterranean Spain demonstrate that reduction of tillage intensity in these areas in cereal crops (Álvaro-Fuentes *et al*., 2009) and in organic almonds trees (Garcia-Franco *et al*., 2015) increase aggregate stability in the soil surface. However, our MWD values showed, according to Le bissonnais (1996), who classified the MWD values in five categories, in both treatments an unstable surface layer, 0.61 mm and 0.76 mm respectively with frequent crusting. It may be due to the fact that management under NT+H system implies the application of pre-emergency herbicides and the maintenance of the bare soil during the year, providing this management low biomass to the soil ecosystem. It is widely known that the deficiency of detritus material due to bare soil maintenance prevents organic material residues and microbial biomes, enhanced SOC therefore both important agents in the aggregation process (Blanco-Canqui and Lal, 2010; Zhang *et al*., 2012; Zhang *et al*., 2016). However, in other studies, management practices associated to reduction of tillage plus a cover (inert or alive) have shown that the increase of grass and residues added to these soils and the degree of decomposition are crucial factors for an increment in the formation and stabilization of aggregates (Garcia-Franco *et al*., 2015; Wang *et al*., 2019).

In fact, the lowest MWD values found in the present study were similar to those found in other areas affected by high erosion rates, degraded soils (Shu *et al*., 2015; Erktan *et al*., 2015) and slope cropland (Zhao *et al*., 2014).

4.2.4.2. Distribution of OC in soil aggregates.

The results of this study implied that there were not important changes in the distribution of OC in the aggregate size classes under CT and NT+H (Figure 4). In both treatments, OC content in the different aggregate fractions followed this order of macroaggregates > microaggregates > silt + clay fraction in the surface horizon (Figure 4a). SOC content gradient suggested a hierarchical succession in the configuration of aggregates (Tisdall and Oades, 1982). This trend continued along the deepest horizons (Figure 4b, 4c, 4d) and the results were consistent with previous studies in which more organic matter content was associated with macroaggregates than with microaggregates and the silt + clay fraction, indicating that macroaggregates are mainly responsible for the improvement of SOC-S (Elliott, 1986; Du *et al*., 2013; Wang *et al*., 2014; Nath and Lal, 2017).

In the surface horizon, in large macroaggregates the highest OC content was detected under NT+H treatment and was significantly reduced in the deeper horizons, this tendency was similar in CT treatment. These results were consistent with the stability of aggregates in this fraction due to macroaggregates in NT+H system were more stable compared to CT (Figure 2). Therefore, NT+H resulted in less disruption of large macroaggregates as the highest MWD demonstrated (Figure 3) as well as the slightly increase in the OC content in this aggregate fraction. These results were in line with other studies (Gao *et al*., 2017; Wang *et al*., 2019). Their analysis show that NT+H is a suitable alternative to increase the stability and the MWD in the topsoil compared to CT. However, NT+H treatment in olive groves did not imply a significant increase in soil aggregation and SOC stabilization, maintaining the problems of low stability and poor values of organic matter. These results were in line with Plaza-Bonilla *et al*. (2010) who conclude the same after a study in cereal crops under Mediterranean semiarid conditions.

In A and B horizons, CT contained 23% more OC content in the small macroaggregates and 5% more OC content in microaggregates fractions than NT+H. This could be explained in part by the redistribution of OC from large macroaggregates to smaller ones, either by the process of mechanical alteration of large macroaggregates, indicating that changes in the tillage system may especially affect C storage and the mechanics within the macro-aggregates (Six *et al*., 2000b; Bhattacharyya *et al*., 2009; Zhang *et al*., 2012). Due to macroaggregates are abundant in labile OC (Wei *et al*., 2013; Kalhoro *et al*., 2017), regular tillage such as CT produces high decomposition of labile OC fractions by breaking macroaggregates into small aggregate-size classes (Six *et al*. 2000a). In addition, CT improves air exchange, which enhances the availability of oxygen for microbial decomposition of organic matter (Wright *et al*., 2007). Therefore, with the rapid removal of the soil profile in the plow layer, aggregate binding agents are destroyed, and thus increase in large macroaggregates OC content is prevented (Yoo and Wander, 2008).

4.2.4.3. SOC stock within aggregate fractions.

Our study found higher SOC-S within aggregate fractions in the upper horizon under CT than in NT+H (11 Mg ha⁻1 *vs.* 7.5 Mg ha^{-1}) (Figure

5). This higher rate into the stable SOC pool aggregates can be attributed to inclusion of organic material into the soil under tillage managements while in NT+H they were left over the soil surface (Plaza-Bonilla *et al*., 2010; Wang *et al*., 2019). Whereas in the deepest horizon, NT+H and CT did not show any significant differences in total aggregate OC stock.

In the surface horizon and considering the different aggregate fractions, CT obtained larger contribution in SOC-S in microaggregate fraction (7.9 Mg ha^{-1}) than NT+H (6.5 Mg ha^{-1}) (Figure 5), which was consistent with the results of many previous studies (Barthes and Roose, 2002; Liang *et al*., 2010; Zheng *et al*., 2018) and a significantly ($P < 0.05$) higher amount of SOC-S in small macroaggregate fraction (2.2 Mg ha^{-1} *vs*. 0.17 Mg ha^{-1}) (Figure 5) (Kumari *et al*., 2011; Devine *et al*., 2014).

However, when we focused our attention on the complete soil profiles there are two different situations. In microaggregate fraction CT obtained lower SOC-S values than NT+H (13.1 Mg ha^{-1} *vs*. 16.0 Mg ha^{-1}) (Figure 5). One reasonable explanation for these results is the higher mass proportion of microaggregates under NT+H treatment (Pinheiro *et al*., 2004). But in small macroaggregates, CT had larger contribution to soil C accumulation than in NT+H (8.3 *vs*. 2.4 Mg ha^{-1}) (Figure 5). A possible reason for these values is the rupture of large macro-aggregates in smaller fractions under tillage management (Grandy and Robertson, 2007) and its incorporation into BW horizon, where CT achieved more than 50% (4.5 Mg ha^{-1}) of the total SOC-S in this fraction in the complete profile (Figure 6). The soil depth evaluated is a crucial aspect to assess the effectiveness of management practices in carbon storage within the aggregate's fractions, in our study subsurface horizons (Bw, BC and C horizons) represented 55.8% under CT and 66.6% under NT+H of the total carbon stored in the profile. These data in line with other recent studies on perennial crops (Bateni *et al.*, 2019; Ledo *et al.*, 2020) demonstrating the relevance of carbon storage in the deeper horizons.

In addition, based on our results, both considering the complete soil profile and all the aggregate fractions together, CT contained 11.2% more SOC-S within aggregate fractions (24.9 Mg ha^{-1}) over NT+H (22.4 Mg ha^{-1}) (Figure 5). Is interesting to focus our attention both in the soil surface and in depth because lots of studies analyze only the surface layer but SOC sequestration depend on the depth which the soil is examined. Therefore, according with our data considering the complete soil profile and other previous studies (Baker *et al*., 2007; Blanco-Canqui and Lal, 2008; Plaza-Bonilla *et al*., 2010) the argument that NT+H management would increase SOC sequestration over CT is questionable also under olive groves in Mediterranean areas.

In depth an interesting trend occurred, while SOC-S within aggregate fractions decreased, the percentage of SOC-S in the macroaggregates fractions increased (Figure 6). This trend in the larger fractions might be related to the increment in structural stability and could benefit C sequestration, although there was a decrease in the total SOC content of the deepest horizons. Therefore, it seems reasonable hypothesize that the distribution of the OC content in the fractions was a key element to determine its influence on the structural stability of the aggregates above of the bulk SOC concentration in the soil (Tisdall and Oades, 1982). Therefore, to understand the mechanisms of SOC sequestration and sink capacity, the analysis of the distribution of the SOC-S in the aggregate fractions is essential (Du *et al*., 2013; Zheng *et al*., 2018).

In addition, associated with this trend, the high carbonate content (Table 1) could influence in the increase in aggregation values, these findings were also observed in other studies in Mediterranean soils (Boix-Fayos *et al*., 2001; Bouajila and Gallali, 2008; Virto *et al*., 2011). The significant role that carbonates take in the particles aggregation is widely recognized, however the high homogeneity of carbonate content (between 29.8 and 37.6%) in both management systems and analyzed horizons makes difficult to attribute changes in aggregate stability to this parameter. This fact suggested that differences in structural stability in depth should have been magnified by other factors such as SOC content distribution even under low SOC levels. Therefore, our data agreed with others (Oades, 1984; Bronick and Lal, 2005) and demonstrated the positive interaction between OC content and carbonates to promote stabilization of soil aggregates. At this point, more research is needed on the relationship between tillage practices and the disposition of OC in aggregate fractions and aggregate stability, especially in the deepest horizons.

4.2.5. Conclusions.

After the long-term of the soil management change, from CT to NT+H, the soil aggregate stability in olive grove did not improve. In the surface horizon (first 21.7 cm in NT+H and 32.7 cm in CT), the absence of tillage improved both small macroaggregates and the MWD. However, these improvements were insufficient to assess the widely accepted concept that the conversion from CT to NT+H management increases soil stability because CT contained more total macroaggregates than NT+H and the values of MWD in CT and NT+H were in the same interval (unstable surface layer). In addition, from 21.7 or 32.7 cm (in NT+H and in CT respectively) onward, CT had larger contribution in values of MWD than NT+H.

NT+H in olive groves neither implied greater SOC stabilization. The adoption of NT+H practice with bare soil did not improved the SOC-S associated with aggregate fractions compared to CT treatment. However, in the upper horizons, NT+H resulted in more OC content and similar SOC-S than CT in large macroaggregates while CT obtained significantly ($P < 0.05$) higher values in small macroaggregates and total macroaggregates. Therefore, in olive groves both managements maintained the problems of low stability and poor values of organic matter.

In depth, in both profiles an increase in stability was detected together with a decrease in the total SOC-S associated with aggregates fractions and an increase in the percentage of SOC-S in the fractions of the macroaggregates. Therefore, these data suggest that the distribution of

SOC in the aggregates had a higher relevance in the stability of the aggregates than the total SOC-S. Therefore, we point out the importance of studying soil in depth, this is considering subsuperficial horizons, because different results and conclusions would have been obtained if the study was focused only in the soil surface.

In rainfed olive groves under Mediterranean conditions, NT + H was not a real alternative to CT due to that management did not improve soil properties or increased the SOC stored within aggregate fractions. Therefore, it is necessary to give advice to farmers about that. In the last decade, lots of olive groves have suffered a transformation related to the management. Farmers changed the intense tillage that maintained soils without weeds by lots of mechanical practices to soils without any mechanical practice but maintaining "clean soils" without weeds by the application of herbicides combined with the crusting of the soil surface that makes it difficult for weeds. This practice of NT+H cannot be considered as a conservation tillage without maintaining any kind of cover (spontaneous vegetal covers, sowed vegetal covers and inert covers). In this case, the use of pruning residues applied each two years was not enough, so it would recommend the use of other cover more.

The widely accepted concept that the conversion of CT to NT+H management increases soil stability and the SOC content has not been demonstrated in this study, mainly due to the complementary practice of bare soil. In addition, with a reduction of the SOC content in depth there was an increase in stability and thus other factors such as soil properties or SOC distribution in the aggregate fractions must be taken in consideration. Therefore, to understand these relationships and interdependences further studies are needed especially in depth where the vast majority of analyses do not examine, together with taking into account the use of covers as an alternative to bare soil.

4.2.6. References.

Abid, M., Lal R., 2008. Tillage and drainage impact on soil quality-I. Aggregate stability, carbon and nitrogen pools. Soil Till. Res., 100, 89–98.https://doi.org/10.1016/j.still.2008.04.012

AEMET – Agencia Estatal de Meteorología, 2020. Standard climate values - Period: 1983-2010. Last accessed (16/03/2020). http://www.aemet.es/en/serviciosclimaticos/datosclimatologicos/valoresclimatologicos?l=5270B&k=and

Aguilera, E., Lassaletta, L., Gattingerd, A., Gimenoe, B., 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. Agriculture, Ecosystems and Environment, 168:25–36. https://doi.org/10.1016/j.agee.2013.02.003

Almaraz, J.J., Zhou, X., Mabood, F., Madramootoo, C., Rochette, P., Ma, B.L., Smith, D.L., 2009. Greenhouse gas fluxes associated with soybean production under two tillage systems in southwestern Quebec. Soil Till. Res., 104, 134-139.https://doi.org/10.1016/j.still.2009.02.003

Álvaro-Fuentes, J., Cantero-Martínez, C., López, M.V., Paustian, K., Denef, K., Stewart, C.E., Arrúe, J.L., 2009. Soil Aggregation and Soil Organic Carbon Stabilization: Effects of Management in Semiarid Mediterranean Agroecosystems. Soil Sci. Soc. Am. J., 73, 1519–1529. https://doi:10.2136/sssaj2008.0333

Álvaro-Fuentes, J., Lóczy, D., Thiele-Bruhn, S., Zornoza,R., 2019. Handbook of plant and soil analysis for agricultural systems (Version 1.0). Zenodo. http://doi.org/10.5281/zenodo.2553445

Ashagrie, Y., Zech, W., Guggenberger, G., Mamo, T., 2007. Soil aggregation, and total and particulate organic matter following conversion of native forests to continuous cultivation in Ethiopia. Soil Till. Res., 94, 101–108. https://doi.org/10.1016/j.still.2006.07.005

Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007.Tillage and soil carbon sequestration - What do we reallyknow? Agr. Ecosyst. Environ., 118,1-5. https://doi.org/10.1016/j.agee.2006.05.014

Barthes, B., Roose, E., 2002. Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. Catena 47: 133–149. https://doi.org/10.1016/S0341-8162(01)00180-1

Bhattacharyya, R., Prakash, V., Kundu, S., Srivastva, A.K., Gupta, H.S., 2009. Soil aggregation and organic matter in a sandy clay loam soil of the Indian Himalayas under different tillage and crop regimes. Agr. Ecosyst. Environ., 132, 126-134. https://doi.org/10.1016/j.agee.2009.03.007

Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A., Ed., Methods of Soil Analysis, Part 1—Physical and Mineralogical Methods, 2nd Edition, Agronomy Monograph 9, Am. Soc. Agronomy–Soil Sci. Soc. Am., Madison, 363-382.

Blanco-Canqui, H., Lal, R., 2008. No-tillage and soil-profilecarbon sequestration: an on-farm assessment. Soil Sci. Soc. Am. J., 72, 693-701. https://doi:10.2136/sssaj2007.0233

Blanco-Canqui, H., Lal, R., 2010. Mechanisms of carbon sequestration in soil aggregates. Crit. Rev. Plant Sci., 23: 481–504. https://doi.org/10.1080/07352680490886842

Boix-Fayos, C., Calvo-Cases, A., Imeson, A.C., 2001. Influence ofsoil properties on the aggregation of some Mediterranean soilsand the use of aggregate size and stability as land degradationindicators. Catena 44, 47– 67. https://doi.org/10.1016/S0341-8162(00)00176-4

Bouajila, A., Gallali, T., 2008.Soil organic carbon fractions and aggregate stability in carbonated and no carbonated soils in Tunisia.J. Agron., 7, pp. 127-137

Brevik, E.C., Cerdà, A., Mataix-Solera, J., Pereg, L., Quinton, JN., Six, J., Van Oost, K., 2015. The interdisciplinary nature of soil. Soil, 1; 117-129. https://doi.org/10.5194/soil-1-117-2015

Briedis, C., Sá, J.C.D.M., Caires, E.F., Navarro, J.D.F., Inagaki, T.M., Boer, A., Neto, C.Q., Ferreira, A.D.O., Canalli, L.B., Santos, J.B.D., 2012. Soil organic matter pools andcarbon-protection mechanisms in aggregate classesinfluenced by surface liming in a no-till system. Geoderma, 170, 80-88. https://doi.org/10.1016/j.geoderma.2011.10.011

Brilli, L., Lugato, E., Moriondo, M., Gioli, B., Toscano, P., Zaldei, A., Leolini, L., Cantini, C., Caruso, G., Gucci, R., Merante, P., Dibari, C., Ferrise, R., Bindi, M., Costafreda-Aumedes, S.,2019. Carbon sequestration capacity and productivity responses of Mediterranean olive groves under future climates and management options. Mitig. Adapt.Strateg. Glob. Change 24, 467–491. https://doi.org/10.1007/s11027-018-9824-x

Bronick, C.J., Lal, R. 2005. Soil structure and management: A review. Geoderma, 124: 3–22.https://doi.org/10.1016/j.geoderma.2004.03.005

Castro, J., Fernández-Ondoño, E., Castro Rodríguez, J., Lallena, A., Sierra, M., Aguilar, J., 2008. Effects of different olive-grove management systems on the organic carbon and nitrogen content of the soil in Jaén (Spain). Soil Till. Res., 98, 56-67. https://10.1016/j.still.2007.10.002

Celik, I., 2005. Land-use effects on organic matter and physical properties of soil in a southern Mediterranean highland of Turkey. Soil Till. Res., 83, 270–277. https://doi.org/10.1016/j.still.2004.08.001

Chenu, C., Le Bissonnais, Y., Arrouays, D., 2000. Organic matter influence on clay wettability and soil aggregate stability. Soil Sci. Soc. Am. J., 64, 1479–1486.https://doi:10.2136/sssaj2000.6441479x

Cotrufo, M.F., Ranalli, M.G., Haddix, M.L., Six, J., Lugato, E., 2019. Soil carbon storage informed by particulate and mineral-associated organic matter. Nat. Geosci. 12, 989–994. https://doi.org/10.1038/s41561-019-0484-6

Devine, S., Markewitz, D., Hendrix, P., Coleman, D., 2014. Soil aggregates and associated organic matter under conventional tillage, notillage,and forest succession after three decades. Plos One 9(1), e84988. https://doi.org/10.1371/journal.pone.0084988

Du, Z.L., Ren, T.S., Hu, C.S., Zhang, Q.Z., Blanco-Canqui, H., 2013. Soil aggregate stability and aggregate-associated carbon under different tillage systems in the North China Plain. J. Integr. Agr., 12, 2114–2123. https://doi.org/10.1016/S2095-3119(13)60428-1

Elliott, E.T., 1986. Aggregate structure and carbon, nitrogen, andphosphorus in native and cultivated soils. Soil Sci. Soc. Am. J., 50 (3), 627–633.https://doi:10.2136/sssaj1986.03615995005000030017x

Erktan, A., Cécillon, L., Graf, F., Roumet, C., Legout, C., Rey, F., 2015. Increase in soil aggregate stability along a Mediterranean successional gradient in severely eroded gully bed ecosystems: combined effects of soil, root traits and plant community characteristics. Plant Soil. 398. https://doi.org/10.1007/s11104-015-2647-6

Eynard, A., Schumacher, T.E., Lindstrom, M.J., Malo, D.D., 2005. Effects of agriculturalmanagement systems on soil organic carbon in aggregates of Ustolls and Usterts.Soil Till. Res. 81, 253–263. https://doi.org/10.1016/j.still.2004.09.012

Fernández-Romero, M.L., Lozano-García, B., Parras-Alcántara, L., Collins, C.D., Clark, J.M., 2016. Effects of land management on different forms of soil carbon in olive groves in Mediterranean areas. Land Degrad.Dev., 27, 1186-1195. http://dx.doi.org/10.1002/ldr.2327

Fernández-Romero, M.L., Parras-Alcántara, L., Lozano-García, B., Clark, J.M., Collins, C.D., 2016. Soil quality assessment based on carbon stratification index in different olive grove management practices in Mediterranean areas. Catena 137, 449–458. https://dx.doi.org/10.1016/j.catena.2015.10.019

Franzluebbers, A.J., 2002. Soil organic matter stratification ratio as an indicator of soil quality. Soil Till. Res., 66, 95-106. https://doi.org/10.1016/S0167-1987(02)00018-1

Gao, L., Becker, E., Liang, G., Houssou, A.A., Wu, H., Wu, X., Cai, D., Degré, A., 2017. Effect of different tillage systems on aggregate structure and inner distribution of organic carbon. Geoderma, 288, 97–104. https://doi.org/10.1016/j.geoderma.2016.11.005

Garcia-Franco, N., Albaladejo, J., Almagro, M., Martínez-Mena, M., 2015. Beneficial effects of reduced tillage and green manure on soil aggregation and stabilization of organic carbon in a Mediterranean agroecosystem. Soil Till. Res., 153, 66-75. https://doi.org/10.1016/j.still.2015.05.010

Grandy, A.S., Robertson, G.P.,2007. Land-use intensity effects on soil organic carbon accumulation rates and mechanisms. Ecosystems, 10, 58– 73. https://doi.org/10.1007/s10021-006-9010-y

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Kalhoro, S.A., Xu, X., Chen, W., Hua, R., Raza, S., Ding, K., 2017. Effects of Different Land-Use Systems on Soil Aggregates: A Case Study of the Loess Plateau (Northern China). Sustainability, 9, 1349. https://doi.org/10.3390/su9081349

Kemper, W.D., Rosenau, R.C., 1986. Aggregate stability and size distribution.p.425-442. In A.Klute (ed.) Methods of soil analysis. Part1.2 inded. Agron.Monogr.9.ASA, Madison, WI.

Kumar, N., Nath, C.P., Hazra, K.K., Das, K., Venkatesh, M.S, Singh, M.K., Singh, S.S., Praharaj, C.S., Singh, N.P., 2019. Impact of zero-till residue management and crop diversification withlegumes on soil aggregation and carbon sequestration. Soil Till. Res., 189, 158–167.https://doi.org/10.1016/j.still.2019.02.001

Kumari, M., Chakraborty, D., Gathala, M.K., Pathak, H., Dwivedi, B.S., Tomar, R.K., Garg, R.N., 2011. Soilaggregation and associated organic carbon fractions as affected by tillage in a rice-wheat rotation in NorthIndia. Soil Sci. Soc. Am. J. 75, 560–567.https://doi.org/10.2136/sssaj2010.0185

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623-1627.https://doi.org/10.1126/science.1097396

Le Bissonnais, Y., 1996. Aggregate stability and assessment of crustability and erodibility: 1. Theory and methodology. Eu. J. Soil Sci., 47, 425-437. https://doi.org/10.1111/ejss.2_12311

Lenka, N.K., Lal, R., 2013. Soil aggregation and greenhouse gasflux after 15 years of wheat straw and fertilizer managementin a no-till system. Soil Till. Res., 126, 78–89.https://doi.org/10.1016/j.still.2012.08.011

Li, H., Ye, X., Geng, Z., Zhou, H., Guo, X., Zhang, Y., Zhao, H., Wang, G., 2016. The influence of biochar type on long-term stabilization for Cd and Cu in contaminated paddy soils. J. Hazard. Mater., 304, 40-48. https://doi.org/10.1016/j.jhazmat.2015.10.048

Liang, A.Z., Yang, X.M., Zhang, X.P., Shen, Y., Shi, X.H., Fan, R.Q., Fang, H.J., 2010. Short-term impacts of no tillage on aggregate-associated C in black soil of Northeast China. Agric. Sci. China, 9, 93–100.https://doi.org/10.1016/S1671-2927(09)60072-9

Lozano-García, B., Parras-Alcántara, L.,2014. Variation in soil organic carbon and nitrogen stocks along a toposequence in a traditional Mediterranean olive grove. Land Degrad. Dev., 25 (3), 297-304.https://doi.org/10.1002/ldr.2284

Lozano-García, B., Muñoz-Rojas, M., Parras-Alcántara, L., 2017. Climate and land use changes effects on soil organic carbon stocks in a Mediterranean semi-natural area. Sci. Total Environ., 579, 1249-1259. https://doi.org/10.1016/j.scitotenv.2016.11.111.

Milgroom, J., Soriano, M.A, Garrido, J., Gómez, J., Fereres, E., 2007. Theinfluence of a shift from conventional to organic olive farming on soil management and erosion risk in southern Spain. Renew. Agr. Food Syst., 22(1), 1-10. http://doi.org/10.1017/S1742170507001500

MITECO, 2017. Inventario nacional de Erosión de Suelos. https://www.miteco.gob.es/es/biodiversidad/temas/inventarios-nacionales/inventario-espanol-patrimonio-natural-biodiv/sistema-indicadores/06d-inventario-erosion-suelos.aspx

Morugán-Coronado, A., Linares P.C., Gómez-López, M., Faz, Á., Zornoza, R.,2020. The impact of intercropping, tillage and fertilizer type on soil and crop yield in fruit orchards under Mediterranean conditions: A meta-analysis of field studies. Agr. Syst., 102736.https://doi.org/10.1016/j.agsy.2019.102736

Nath, A.J., Lal, R., 2017. Effects of tillage practices and land use management on soil aggregates and soil organic carbon in the north Appalachian region, USA. Pedosphere, 27(1), 172–176.https://doi.org/10.1016/S1002-0160(17)60301-1

Nelson, D.W., Sommer, L.E., 1982. Total Carbon, Organic Carbon and Organic Matter. Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties, 2nd Edition. ASA-SSSA, Madison, 595-579.

Oades, J.M., 1984. Soil organic matter and structural stability: mechanisms and implications for management.Plant Soil 76, 319–337. https://doi.org/10.1007/BF02205590

Pastor, M., 2004. Sistemas de manejo de suelo. En: El cultivo del olivo (Barranco D, Fernández-Escobar R, Rallo L, eds). Mundi Prensa, Madrid. pp: 231-285.

Pinheiro, E.F.M., Pereira, M.G., Anjos, L.H.C., 2004. Aggregate distribution and soil organic matter under different tillage systems for vegetable crops in a Red Latosol from Brazil. Soil Till. Res., 77, 79–84. https://doi.org/10.1016/j.still.2003.11.005

Plaza-Bonilla, D., Cantero-Martínez, C., Álvaro-Fuentes, J., 2010. Tillage effects on soil aggregation and soil organic carbon profile distribution under Mediterranean semi-arid conditions. Soil Use Manage., 26. 465-474. https://doi.org/10.1111/j.1475-2743.2010.00298.x

Salomé, C., Nunan, N., Pouteau, V., Lerch, TZ.,Chenu, C., 2010. Carbon dynamics in topsoil and in subsoil may be controlled by different regulatory mechanisms. Glob. Change Biol., 16, 416-426. https://doi.org/10.1111/j.1365-2486.2009.01884.x

Sastre, B.E., Marqués, M.J., García-Díaz, A., Bienes, R., 2018. Three years of management with cover crops protecting sloping olive groves soils, carbon and water effects on gypsiferous soil.Catena. 171. 115-124. https://doi.org/10.1016/j.catena.2018.07.003

Shu, X., Zhu, A., Zhang, J., Yang, W., Xin, X., Zhang, X., 2015. Changes in soil organic carbon and aggregate stability after conversion to conservation tillage for seven years in the Huang-Huai-Hai Plain of China. J. Integr. Agr., 14, 1202-1211. https://doi.org/10.1016/S2095-3119(14)60862-5

Six, J., Elliott, E.T., Paustian, K., 2000a. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem., 2, 2099-2103.https://doi.org/10.1016/S0038-0717(00)00179-6

Six, J., Paustian, K., Elliott, E.T., Combrink, C., 2000b. Soil structure and soil organic matter: I. Distribution of aggregate size classes and aggregate associated carbon. Soil Sci. Soc. Am. J., 64, 681-689. https://doi.org/10.2136/sssaj2000.642681x

Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil Till. Res., 79, 7-31.https://doi.org/10.1016/j.still.2004.03.008

Six, J., Elliott, E.T., Paustian, K., 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. 63, 1350–1358.https://doi.org/10.2136/sssaj1999.6351350x

Six, J., Elliott, E.T., Paustian, K., Doran, J.W., 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci. Soc. Am. J., 62, 1367– 1377. https://doi.org/10.2136/sssaj1998.03615995006200050032x

Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. J Soil Sci. 62: 141–163.https://doi.org/10.1111/j.1365-2389.1982.tb01755.x

Virto, I., Gartzia-Bengoetxea, N., Fernández-Ugalde, O., 2011. Role of organic matter and carbonates in soil aggregation estimated using laser diffractometry. Pedosphere. 21,566–572. https://doi.org/10.1016/S1002-0160(11)60158-6

Wang, B., Gao, L., Yu, W., Wei, X., Li, J., Li, S., Song, X., Liang, G., Cai, D., Wu, X., 2019. Distribution of soil aggregates and organic carbon in deep soil under long-term conservation tillage with residual retention in dryland. J. Arid Land. 11. 241-254. https://doi.org/10.1007/s40333-019-0094-6

Wang, H., Guan, D., Zhang, R., Chen, Y., Hu, Y., Xiao, L., 2014. Soil aggregates and organic carbon affected by the land use change from rice paddy to vegetable field. Ecol. Eng., 70. 206–211. https://doi.org/10.1016/j.ecoleng.2014.05.027

Wei, X., Li, X., Jia, X., Shao, M., 2013. Accumulation of soil organic carbon in aggregates after afforestation on abandoned farmland. Biol. Fertil. Soils, 49, 637–646. https://doi.org/10.1007/s00374-012-0754-6

Wright, S.F., Green, V.S., Cavigelli, M.A., 2007. Glomalin in aggregate size classes from three different farming systems. Soil Till. Res., 94, 546–549.https://doi.org/10.1016/j.still.2006.08.003

Xie,J.Y., Xu, M.G., Qiangjiu,C.R., Yang,Y., Zhang, S.L., Sun,B.H., Yang,X.Y., 2015. Soil aggregation and aggregate associated organic carbon and total nitrogen under long-term contrasting soil management regimes in loess soil. J. Integr. Agr., 14 (12), 2405-2416.https://doi.org/10.1016/S2095-3119(15)61205-9

Yoo, G., Wander, M.M., 2008. Tillage Effects on Aggregate Turnover and Sequestration of Particulate and Humified Soil Organic Carbon. Soil Sci. Soc. Am. J., 72, 670-676. https://doi.org/10.2136/sssaj2007.0110

Zhang, S., Wang, R., Yang, X., Sun, B., Li, Q., 2016. Soil aggregation and aggregating agents as affected by long term contrasting management of an Anthrosol. Sci. Rep., 6, 1–11. https://doi.org/10.1038/srep39107

Zhang, S., Li, Q., Zhang, X., Wei, K., Chen, L., Liang W., 2012. Effects of conservation tillage on soil aggregation and aggregate binding agents in black soil of Northeast China. 2012. Soil Till. Res., 124, 196-202. https://doi.org/10.1016/j.still.2012.06.007

Zhao, F., Han, X.H., Yang, G.H., Feng, Y.Z., Ren, G., 2014. Soil structure and carbon distribution in subsoil affected by vegetation restoration. PlantSoil Environ., 60, 21-26. https://doi.org/10.17221/353/2013-PSE

Zheng, H., Liu, W., Zheng, J., Luo, Y., Li, R., Wang, H., Qi, H., 2018. Effect of long-term tillage on soil aggregates and aggregate-associated carbon in black soil of Northeast China. PLOS ONE. 13(6). e0199523. https://doi.org/10.1371/journal.pone.0199523

Zomer, R.J., Bossio, D.A., Sommer, R., Verchot, L.V., 2017. Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. Sci. Rep., 7, 15554. https://doi.org/10.1038/s41598-017-15794-8

Short-term effects of land management change linked to cover crop on soil organic carbon in Mediterranean olive grove hillsides.

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Short-term effects of land management change linked to cover crop on soil organic carbon in Mediterranean olive grove hillsides

Manuel González-Rosado, Beatriz Lozano-García, Jesús Aguilera-Huertas, Luis Parras-Alcántara *

SUMAS Research Group, Department of Agricultural Chemistry and Soil Science, Faculty of Science, Agrifood Campus of International Excellence - ceiA3, University of Cordoba, 14071 Cordoba, Spain

HIGHLIGHTS

- In short-term land management affect to soil organic matter distribution.
- To study the topographic position is important on SOC variation in Mediterranean areas.
- Good environment practices are an opportunity to soils regeneration.
- Conventional tillage - highly intensified causes strong water erosion and soil decarbonization.

GRAPHICAL ABSTRACT

4.3.1. Introduction.

The Mediterranean basin is characterized mainly by three natural factors: (i) the climate, with moderate rainfall in winter and hot and dry months of summer, drying up the soils - xeric moisture regime (Cowling *et al.*, 2005), (ii) the landscape, formed by steep slopes with slight changes in concavity and convexity (Conforti *et al.*, 2020) and (iii) the lithology, with a large proportion of limestone and other calcareous rocks (Yaalon, 1997). As a consequence of these three factors, the weathering is moderate, forming B horizons of clayey nature, due to different processes (leaching, dehydration, dissolution and reprecipitation with calcic horizon prevalence), developing shallow soils on almost bare hillsides mainly due to erosion processes (Yaalon, 1997). According to these conditions, the soils diversity that can formed is highly variable (Olaya-Abril *et al.*, 2017a), highlighting, Cambisols, Leptosols, Luvisols, Regosols, Luvisols, Fluvisols, Vertisols and Phaeozems (IUSS Working Group WRB - FAO, 2015), developed in different physiographic positions (Crest, Depression, Hill, Hillside, Plateau, Plain, Terrace and Valley) in different surrounding topography (Flat, Hilled, Steep and Wavy) (Olaya-Abril *et al.*, 2017b) and associated with different land use types (Meadow, Bushland, Broadleaved forest, Coniferous forest, Pasture, Irrigated farming, Dryland farming, Olive grove (OG) and Vineyard) (Rodriguez-Murillo, 2001).

This Mediterranean soils diversity together with an intensive tree cultivation in Mediterranean soils, in many cases generates land degradation and soil loss quality (Parras-Alcántara *et al.*, 2016; Morugán-Coronado *et al.*, 2020) by reduction and depletion of soil organic matter (SOM) and soil organic carbon (SOC) linked to erosive processes (Muñoz-Rojas *et al.*, 2015), influenced by vegetation cover reduction due to climatic conditions and land management (very aggressive with the soil and strongly intensified) as it happens in OG and vineyards (Francaviglia *et al.*, 2018).

In this respect, the OG is the main agricultural use in Mediterranean areas with more than 5 Mha (López-Piñeiro *et al.*, 2011). But this OG development in Mediterranean areas has negative consequences for the soil, as OG soils are characterized by a low organic matter (OM) contents (<2%) (Trigo *et al.*, 2009) and, therefore, it would be necessary to act on them to increase the SOM content and to improve the soil quality (Fernández-Romero *et al.*, 2016a). This low SOM content is caused by heavy soil losses (water erosion) due to management techniques (very intensified tillage), slope and low density of trees (Cerdà *et al*., 2010), which facilitates the agricultural soils degradation (García-Orenes *et al*., 2012). At the beginning of the 20th century, the OG was located on flat surfaces, but later due to subsidies and good olive oil prices, the OG has been planted in much more complex topographies (Lozano-García and Parras-Alcántara, 2014) causing serious problems of soil loss (water erosion).

The topographical position plays an important role with regard to soil temperature and humidity regimes, due to differences in the sunstroke period, which affect to the microclimate development (Griffiths *et al*., 2009), and differences in microclimate affect to plant communities distribution, as well as to soil formation processes (Bochet, 2015). Therefore, the topography can affect to SOC distribution (Parras-Alcántara *et al*., 2015a), either by delaying or accelerating the SOC decomposition by affecting the microorganism's activity through their influence on soil temperature and water content (Scowcroft *et al*., 2008). In this line, the combined effects of land use, tillage, and topographical position can affect to SOC accumulation in eroded regions (Schwanghart and Jarmer, 2011).

The carbon (C) transfers can occur between the terrestrial and atmospheric reservoirs (McDonough, 2016) in response to natural processes: photosynthesis, soil breathing and erosive processes (Lal, 2016). Hence, the soil can act as C sink or as C source, becoming a fundamental and necessary component of the climate system (AEMA, 2015; Caviglia *et al*., 2016; Lal, 2010). Land use change (LUC) is the second greatest cause of C emissions after fossil fuel consumption (Smith, 2008) due to soil degradation and SOC losses, and this fact is especially important in semiarid regions as the Mediterranean areas (Eaton *et al*., 2008; Cerdà *et al*., 2010). The recent approach to optimize the efficiency of C sequestration in agriculture is the mixed systems such: crop diversification, crop rotation, intercropping, cover cropping etc. These new agricultural systems play a critical role as they contribute to increase the agricultural production and they also improve the SOC content due to the increase in biomass that remains in the soil (*Ghosh et al*., 2018).

There are a wide variety of studies evaluating possible solutions to this problem, mainly focused on the development of new management techniques (Milgroom *et al*., 2007; Gómez *et al*., 2009; Parras-Alcántara *et al*., 2016) and estimating trends in hillsides altitudinal gradients (Avilés-Hernández *et al*., 2009; Costa *et al*., 2015), but most of these studies are focused on forest areas and not on agricultural land (Lozano-García and Parras-Alcántara, 2014).

In addition to this, we need to keep in mind that the SOC reduction is one of the eight soil threats identified in the European Union (EU) Thematic Strategy for Soil Protection (E.C, 2006, E.C, 2012), and therefore one of the most important aims is to maintain and improve the SOC stock (SOC-S) throughout the EU countries. The Roadmap to a Resource Efficient Europe (EC, 2011), established the goal of enhancing current SOC levels in the EU by 2020 (Lugato *et al*., 2014). Also, under Common Agricultural Policy (CAP), farmers are called up to maintain the agro-ecosystem by rural development measures coupled with the environmentally sustainable farming practices promotion. Therefore, farmers must achieve soil erosion protection, soil structure maintenance and soil OM levels under the EU cross-compliance scheme (Lugato *et al.*, 2014). Under this scenario, the soil carbon studies will be linked to factors such as: soil health, ecosystem services and, derived from this, economic implications. And, therefore, it will be necessary to carry out short-term studies of the SOC and SOC-S to estimate its variations (positive or negative). In addition, many studies on SOC that were made many years ago (40, 50 …), they are not representative, since the climatic conditions are different from the current ones (based on the idea that soil carbon derives from the organic matter degradation, and this depends on climatic conditions). Therefore, to obtain satisfactory and comparable results, we need short-term studies, where the environmental conditions are preferably homogenous and with similar calculation methods.

The main goal of this research was to determine the effects in the soil organic carbon, nitrogen and stock in a hillsides, as well as other physical soil properties, evaluating the land management change effects (from conventional to no tillage with spontaneous plant covers) considering soil entire profile in olive grove soils in three topographical position (summit, backslope and toeslope) in Mediterranean areas in short term (2 years), to assess the carbonization, the recarbonization or the decarbonization processes in the soil.

4.3.2. Materials and methods.

4.3.2.1. Study area.

The study was carried out in Garcíez-Torredelcampo-Jaén (37°50′20″N - 3°52′32″W; with an average altitude of 541 m.a.s.l. - ranging from 530 m.a.s.l. to 593 m.a.s.l. - meters above sea level) (Figure 1). The OG was oriented S-SW, and it is characterized by denudative morphogenesis, formed by hills with moderate denudative influence (De la Rosa and Moreira, 1987). The relief was smooth with slopes ranging from 1% to 6% and may reach values of 8%. The parent materials were Miocene marl and marlaceous lime (Fernández-Romero *et al*., 2016a). The climate was Mediterranean (Csa) according to the Köppen-Geiger updated classification (Kottek *et al*., 2006) with 3–5 months of summer drought (June to September), and moderately wet cool winters. The annual average temperature was 17.1 °C, with a maximum air temperature of 46.2 °C in August and a minimum air temperature of −7.8 °C in January. The annual average precipitation was 493.2 mm, and monthly rainfall ranges from 2.1 mm (July) to 75 mm (December) - all data for the period 1983–2010 (AEMET, 2020).

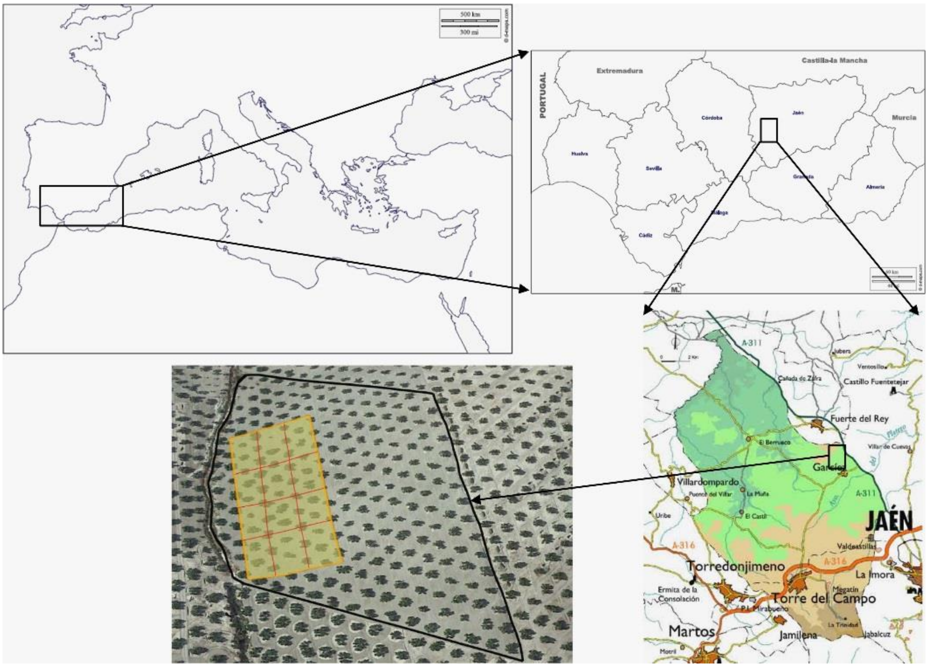


Figure 1. Study area. Garcíez-Torredelcampo (Jaén-Spain) (37°50′20″N - 3°52′32″W).

The representative soils were Calcaric Cambisols (CMcc) with some vertic characteristic according to IUSS Working Group WRB (FAO, 2015) or calcixerolic Xerochrept according to Soil Taxonomy (Soil Survey Staff, 2014). In general, the soils were characterized by low fertility, poor physical conditions, and marginal capacity for agricultural use (Fernández-Romero *et al*., 2016b). The vegetation was a centenary traditional rainfed OG (*Olea europaea*) of the Picual variety with traditional management (strongly mechanized) (Figure 2).

4.3.2.2. Experimental design.

The study was carried out from September 2017 until September 2019, in a centenary OG with an average density of 90 trees ha^{-1} (each tree had two trunks), with a uniform tree spacing (12 m × 12 m) and tree size (3 m high × 6 m canopy diameter). The OG tillage was traditional management (heavily tilled) - conventional tillage (CT), with 100 kg ha^{-1} of mineral fertilizer (urea, 46% N) applied in alternate years during winter, just after the harvest. In addition, a broad-spectrum herbicide was added in autumn to control weeds under trees to allow the harvest of the olives. Lastly, an annual pass with a disk harrow and cultivator in the spring, followed by a tine harrow in summer were used to control weeds (Figure 2).

Figure 2. Images of two study plots in Torredelcampo - Jaén. The picture on the left shows Conventional tillage (Initial situation - September 2017) and the image on the right is No tillage (Final situation - September 2019).

In September of 2017 three plots in different topographical positions: summit (S), backslope (B) and toeslope (T) on a hillside were selected for the study (Figure 1, Figure 2, Figure 3), each plot had an area of 2400

m^2 (200 m × 12 m). In these plots, the land management was modified - changed (LMC). The alternative management developed to improve the soil quality in the three topographical positions (S - B - T) was: no tillage (NT-CC) with application of pruned olive branch chippings branches (6 Mg ha^{-1}) and vegetation cover (spontaneous vegetation) in the streets, also, no weed control was used (no herbicides were used) in two successive years (from September 2017 until September 2019) (Figure 2).

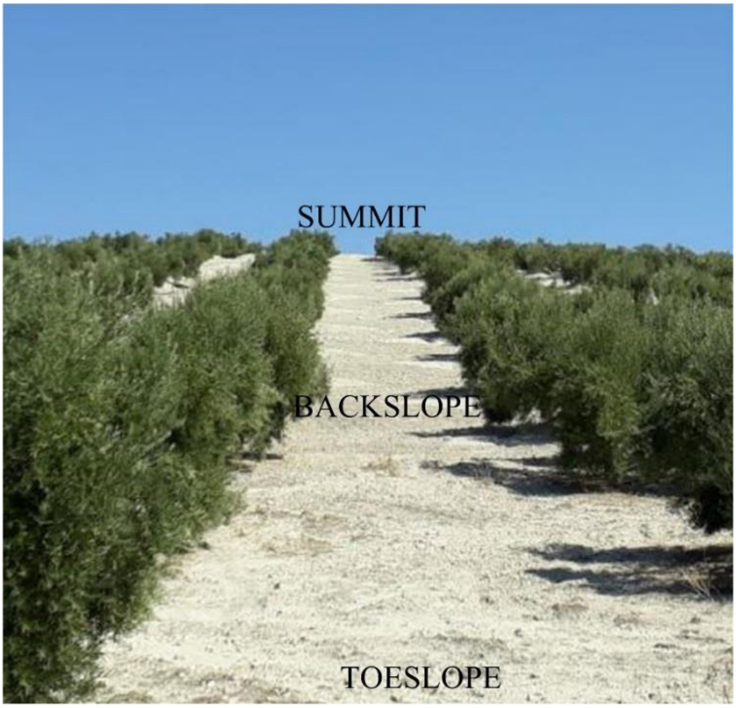


Figure 3. Experimental site and schematic topographical position.

4.3.2.3. Soil sampling, analytical methods, and statistical analyses.

Samples from 18 soil entire profiles were collected [9 in CT at the beginning of the experiment (September 2017) and 9 in NT-CC at the end of the experiment (September 2019); 3 in each topographical position (S – B – T) in both cases (CT and NT-CC)] (3 soil profiles × 2 managements × 3 topographical positions = 18 soil entire profile) (Figure 3).

Soil samples were collected along the different soil horizons for each profile, thus avoiding the mixing of the pedogenic horizons and allowing for a proper determination of physical and chemical soil properties (Lal, 2005; Parras-Alcántara *et al*., 2015b; Francaviglia *et al*., 2017). A random sampling scheme was adopted, pits were digged with a mini excavator, and samples for a general characterization of entire soil profiles were collected along the different soil horizons.

Samples were dried at a constant room temperature (25 °C) and sieved (2 mm). The remaining gravel was weighed. Three laboratory replications were performed for each soil sample. The analytical methods used in this study to determine different soil properties are reported in Table 1, according to handbook of plant and soil analysis for agricultural systems (Álvaro-Fuentes *et al*., 2019).

Parameters	Method
Field measurements	
Bulk density (Mg m^{-3})	Core method (Blake and Hartge, 1986)[a]
Laboratory analysis	
Particle size distribution	Bouyucus method (USDA, 2004)[b]
pH – H_2O	Suspension in water 1:2.5 (Guitián and Carballas, 1976)
Organic C (g kg^{-1})	Walkley and Black method (Nelson and Sommers, 1982)
Total N (g kg^{-1})	Kjeldahl method (Bremner, 1996)
Parameters calculated	
SOC-S (Mg ha^{-1})	SOC-S = SOC concentration × BD × d × (1 –
T-SOC-S (Mg ha^{-1})	T-SOC-S = $\Sigma_{\text{soil horizon } 1\ldots n}$ SOC-S $_{\text{soil horizons}}$ (IPCC,

Table 1. Analytical methods used in this study (field measurements, laboratory analysis and parameters calculated). For all the parameters studied, the recommendations of the Handbook of Plant and Soil Analysis for Agricultural Systems have been followed (Álvaro-Fuentes *et al*., 2019).

a. 3 cm in diameter, 10 cm in length and 70.65 cm^3 in volume.

b. Prior to determination of particle size distribution, samples were treated with H_2O_2 (6%) to remove organic matter (OM). Particles larger than 2 mm were determined by wet sieving and smaller particles were classified according to USDA (2004) standards.

c. Where SOC is the organic carbon content (g kg^{-1}), d the thickness of the soil layer (cm), δ2 mm is the fractional percentage (%) of soil mineral particles >2 mm in size in the soil, and BD the soil bulk density (Mg m^{-3}).

d. T-SOC-S: Total SOC stock determined by adding all the soil horizons considered.

The effect of topographical position and land management on soil properties was analyzed using ANOVA (SPSS 13.0 for Windows). Data were tested for normality to verify the model assumptions, and differences of $p < 0.05$ were considered statistically significant.

4.3.3. Results and discussion.

4.3.3.1. Basic soil properties.

The soil studied were CMcc with some vertic characteristic according to IUSS Working Group WRB (FAO, 2015) or calcixerolic Xerochrept according to Soil Taxonomy (Soil Survey Staff, 2014), showing some differences in their physical and chemical properties with respect to management (CT – NT-CC) and topographic position (S - B - T) (Lozano-García and Parras-Alcántara, 2014; Lozano-García *et al*., 2017) (Table 2). An important characteristic of this soils type is that they do not derive from the physiography position directly, they are formed from the bedrock (marl and marlaceous lime) and their development is mainly conditioned by their limestone genesis, being the Ca^{2+} ion that conditions them (Alcaide, 2013). They are young soils develops on hillsides slightly undulating, well drained, presenting a horizon sequence Ap/Bw/C and characterized by low fertility, poor physical conditions, and a marginal capacity for agricultural uses (Parras-Alcántara and Lozano-García, 2014).

T-P	M	Hor	Depth (cm)	Th (cm)	Gravel (%)	Text	Sand (%)	Silt (%)	Clay (%)	BD (Mg m⁻³)	pH (H_2O)
Summit	CT	Ap	0-23.4	23.4±4.2Aa	19.12±3.56Aa	C	7.13±2.32Aa	22.81±3.26Aa	70.06±4.25Aa	1.36±0.07Aa	7.91±0.10Aa
	n=3	Bw	23.4-56.9	33.5±6.2Aa	10.47±5.14Aa	C	8.71±3.25Aa	22.93±4.31Aa	68.36±6.58Aa	1.38±0.03Aa	8.00±0.10Aa
		Bw/C	56.9-82.6	25.7±4.6Aa	23.14±2.02Aa	C	6.65±4.26Aa	25.01±3.28Aa	68.34±4.36Aa	1.37±0.04Aa	8.22±0.05Aa
		C	82.6-123.8	41.2±8.9Aa	32.64±0.28Aa	C	10.18±3.25Aa	21.42±2.14Aa	68.40±4.18Aa	1.39±0.02Aa	8.15±0.13Aa
	NT	Ap	0-23.4	23.4±4.2Aa	8.65±1.87Ba	C	5.71±2.67Ba	22.59±4.56Aa	71.70±5.67Aa	1.33±0.04Aa	7.79±1.45Aa
	n=3	Bw	23.4-56.9	33.5±6.2Aa	8.59±2.05Aa	C	8.30±1.84Aa	21.00±3.13Aa	70.70±3.40Aa	1.48±0.05Ba	7.71±0.56Aa
		Bw/C	56.9-82.6	25.7±4.6Aa	25.18±3.67Aa	C	6.63±2.16Aa	25.43±3.92Aa	67.94±4.23Aa	1.37±0.02Aa	8.20±0.76Aa
		C	82.6-123.8	41.2±8.9Aa	28.32±3,22Aa	C	10.22±2.53Aa	22.03±2.95Aa	67.75±2.98Aa	1.39±0.04Aa	8.23±0.79Aa
Backslope	CT	Ap	0-27.8	27.8±3.6Ab	12.00±3.89Ab	C	5.35±3.25Aa	21.13±4.74Aa	73.52±2.36Aa	1.33±0.07Ab	7.73±0.10Aa
	n=3	Bw	27.8-59.2	31.4±6.4Aa	20.72±4.87Ab	C	0.92±4.18Ab	21.17±2.18Aa	77.91±1.25Ab	1.34±0.03Ab	8.21±0.10Aa
		Bw/C	59.2-85.0	25.8±3.8Aa	25.17±3.24Aa	C	9.96±3.68Aa	21.47±3.25Aa	68.57±3.29Aa	1.39±0.04Aa	8.11±0.05Aa
		C	85.0-124.6	39.6±5.7Aa	28.13±1.95Aa	C	10.24±2.56Aa	21.77±2.36Aa	67.99±3.47Aa	1.40±0.02Aa	8.00±0.13Aa
	NT	Ap	0-27.8	27.8±3.6Aa	10.81±1.34Ab	C	10.48±2.87Bb	20.50±3.48Aa	69.02±3.87Aa	1.27±0.05Bb	7.79±0.92Aa
	n=3	Bw	27.8-59.2	31.4±6.4Aa	11.09±2.76Bb	C	9.82±2.95Ba	18.64±2.97Aa	71.54±4.69Ba	1.38±0.04Bb	7.75±1.17Aa
		Bw/C	59.2-85.0	25.8±3.8Aa	22.11±3.34Aa	C	9.87±1.64Aa	21.87±3.65Aa	68.26±3.58Aa	1.39±0.07Aa	8.11±1.78Aa
		C	85.0-124.6	39.6±5.7Aa	26.56±4.14Aa	C	10.42±3.23Aa	21.70±2.84Aa	67.88±4.21Aa	1.40±0.03Aa	8.00±0.97Aa
Toeslope	CT	Ap	0-35.9	35.9±3.6Ac	15.84±4.18Ab	C	15.16±4.36Ab	13.51±3.25Ab	71.33±6.25Aa	1.33±0.07Ab	7.81±0.10Aa
	n=3	Bw	35.9-66.2	30.3±4.5Aa	16.20±3.25Ab	C	1.35±0.25Ab	18.98±3.45Aa	79.67±3.48Ab	1.33±0.03Aa	8.11±0.10Aa
		Bw/C	66.2-90.4	24.2±2.6Aa	22.11±3.89Aa	C	2.79±1.25Ab	15.41±5.61Ab	81.80±3.42Ab	1.34±0.04Aa	8.20±0.05Aa
		C	90.4-128.7	38.3±5.3Aa	20.29±2.31Ab	C	9.16±2.36Aa	21.67±2.34Aa	69.17±4.22Aa	1.37±0.02Aa	8.25±0.13Aa
	NT	Ap	0-35.9	35.9±3.6Ab	6.80±1.23Ba	C	6.98±2.64Bb	21.94±4.54Ba	71.08±4.67Aa	1.19±0.04Bc	7.78±0.67Aa
	n=3	Bw	35.9-66.2	30.3±4.5Aa	9.75±1.92Ba	C	6.27±1.78Bb	21.08±3.47Aa	72.65±5.23Ba	1.37±0.03Ab	7.84±0.89Aa
		Bw/C	66.2-90.4	24.2±2.6Aa	21.56±2.45Aa	C	2.84±0.67Ab	15.34±2.64Ab	81.82±4.85Ab	1.35±0.02Aa	8.23±1.17Aa
		C	90.4-128.7	38.3±5.3Aa	19.97±3.34Ab	C	9.22±1.65Aa	22.36±3.76Aa	68.42±3.56Aa	1.38±0.07Aa	8.27±4.67Aa

Table 2. Principal soil properties evaluated (average ± SD*) in the entire soil profile by horizons in the study area. Conventional tillage (Initial situation - September 2017), No tillage (Final situation - September 2019). SD*: Standard deviation; T-P: Topographic position; M: Management; Hor: Horizon; Th: Thickness; Text: Texture (USDA, 2004); C: Clayey; BD: Bulk density; OM: Organic matter. CT: Conventional tillage; NT: No tillage; *n* = Sample size.
Numbers followed by different capital letters are significantly different ($p < 0.05$) for the same horizon among different management (CT-NT) in the same topographical position.
Numbers followed by different lower-case letters are significantly different ($p < 0.05$) for the same horizon among different topographical position (Summit-Backslope-Toeslope) considering the same management (CT – NT).

In general, they were not very deep soils (123.8–128.7 cm), similar outcomes were obtained by Fernández-Romero *et al*. (2016b) in CM in Mediterranean areas for rainfed OG, found no significant difference ($p < 0.05$) regarding soil depth, with values in the range 119.7–128.7 cm and where depth was limited by rock fragments. Regarding to soil horizons thickness, no significant changes ($p < 0.05$) had occurred in relation to management (CT – NT-CC) or topographic position (S - B - T) in the study period (2 years), and the slight variations can be justified due to slope steepness, length, topographic curvature and relative topographic position regarding to different soil positions (Parras-Alcántara *et al*., 2013).

The gravel content was very homogeneous in soil horizons, with low and medium gravel content ranging from 6.8% (Ap horizon-NT-CC-T) to 32.6% (C horizon-CT-S) (Table 2), and no significant differences ($p < 0.05$) were found between management and topographic position except for top soil (Ap horizon) in S and T. In general, the trend was to increase in depth except for T position that decreased in C horizon. This behavior may be due to the stone line presence as postulated Symith and Montgomery (1962) and because the tillage used does not remove large stones and boulders (Fernández-Romero *et al*., 2014). Also, when the gravel content is high, retard ponding and surface runoff, increase steady-state infiltration rates and diminished runoff discharge, sediment concentrations and erosion rates, enhance the water percolation and reduce the erosion by curbing erodibility and runoff (Cerdá, 2001). It is important to point out that soil gravel content is a very important factor affecting to SOC-S estimation. In this line, IPCC (2003) and Stolbovoy et al., 2005, Stolbovoy *et al.*, 2007 in soil sampling protocol indicates that the gravel content should be considered in the SOC-S quantifications.

Texturally the soils were clayey, regarding the textural behavior along the hillside. In this lines, it is important to highlight that there were no significant differences ($p < 0.05$) in the silt content in the three topographic positions (S - B - T), however, there was a reduction in the sand content from highest positions (S) to slope lower parts (T), but nevertheless, the clays content increases in the opposite direction (Table 2). These results were contrary to those found by Lozano-García and Parras-Alcántara (2014) in Mediterranean OG soils toposequence, that they show an increasing in silt fraction in T position consequence of the silt's high erodibility. However, as we can see in Table 2, the clay content increased normally in depth from the top to the bottom on the slope (descending direction), this may be due to more intense subsoil weathering, which were more significant in the positions with lowest slope compared to the highest slope parts (Figure 3). This could be due to increase of moisture availability in lowest positions caused by concave surfaces. Furthermore, in arid environments, the humidity could also to increase the clay content at lower topographic positions, which explains the increase in clay content. These results are in line with Nizeyimana and Bicki (1992), who indicated that the clay content increases with soil depth and along the descending direction due to the superficial movement of the clay along the slope on surface and simultaneously a clay translocation along the profile. However, in some cases we could observe increases in clay content on surface (Ap horizon-S) (Table 2), this may be due to the surface horizon truncation when at depth there are horizons rich in clay. In this line, De Alba *et al*. (2004) reported that soil truncation occurs on convex slopes in the upper slope positions due to soil erosion.

For all topographical positions, bulk density (BD) increased in depth (Table 2), although generally no major changes occur, ranging from 1.19 Mg m^{-3} (Ap horizon-NT-CC-T) to 1.48 Mg m^{-3} (Bw horizon-NT-CC-S). Significant differences ($p < 0.05$) were found in terms of management, producing a BD reduction in NT-CC with respect to CT in the different topographic positions, being significant these changes in the surface horizon (Ap horizon), this effect may be due to SOM increase. Other authors have found similar or increased values in BD in the first centimeters of soil after short-term studies of NT (Puget and Lal, 2005; Al-Kaisi *et al*., 2005). By contrast, Tebrügge and Düring. (1999) indicated that BD generally increased superficially under NT-CC, although decreased in the soil surface, the reason is that NT-CC provide OM and food for soil fauna, which loosens surface soil through burrowing activities.

In general, the soils studied were basic (pH > 7), varying between 7.71 (Bw horizon-NT-CC-S) and 8.27 (C horizon-NT-CC-T), with no significant differences ($p < 0.05$) in relation to topography or management, but characterized by increasing pH in depth. In this line, Zhang *et al*. (2019) indicates that soil pH is conditioned by topography (topography control water flow and material transport and by changing the local climate - low temperature and abundant rainfall), climate (soils from arid climates are commonly alkaline with high soil pH) and lithology (parent material is the most essential factor that affected soil pH). Therefore, in hillside with Mediterranean semiarid climate and with calcareous nature (parent materials), the pH should increase in depth as indicated our data (Table 2).

4.3.3.2. Organic matter, soil organic carbon, and stock. State of the art in the studied soils.

With respect to OM, firstly we observed a reduction in depth in all cases (management and topographic positions), secondly we observed relatively low values increasing their concentrations as we descend along the hillside (Table 3 and Figure 4), and varying with management in surface horizon between 0.60% (Ap horizon-NT-CC-S) and 1.20% (Ap horizon-CT-T). These low OM concentrations can be explained by the semiarid Mediterranean characteristics (Gallardo *et al.*, 2000), by the high OM mineralization by the lack of crop residues after periods of drought (Hernanz *et al.*, 2009) and by degradation processes due to the vegetation loss and unsustainable soil management, causing an impoverishment in the SOM content, affecting to soil productivity. Due to this, the SOC concentrations were also low, as a consequence of the low SOM content, affecting to the soil physical protection favoring the erosion processes and accelerating the decomposition rate due to CT (intense tillage) (Jordán *et al.*, 2010; Moscatelli *et al.*, 2007).

T-P	M	Hor	OM %	SOC (g kg^{-1})	SOC-S (Mg ha^{-1})	N (g kg^{-1})	N-S (Mg ha^{-1})	C:N
Summit	CT1 *n=3*	Ap	0.61±0.17Aa	3.21±0.18Aa	8.26±6.72Aa	0.61±0.34Aa	1.57±1.46A	5.27±0.84Aa
		Bw	0.48±0.18Aa	2.59±0.11Aa	10.72±1.19Aa	0.30±0.18Aa	1.24±0.47A	8.64±0.78Aa
		Bw/C	0.49±0.14Aa	2.57±0.08Aa	6.95±2.74Aa	0.42±0,14Aa	1.14±0.37A	6.12±0.54Aa
		C	0.30±0.11Aa	1.58±0.10Aa	6.10±4.32Aa	0.42±0.13Aa	1.62±0.75A	3.77±0.82Aa
	NT *n=3*	Ap	0.60±0.15Aa	3.16±0.65Aa	8.98±1.23Aa	0.61±0.18Aa	1.73±0.34A	5.19±0.56Ba
		Bw	0.53±0.09Ba	2.79±0.94Ba	12.65±1.56Ba	0.53±0.24Ba	2.45±0.21B	5.27±0.67Ba
		Bw/C	0.49±0.13Aa	2.58±1.01Aa	6.80±0.96Aa	0.42±0.15Aa	1.14±0.28A	6.15±0.49Aa
		C	0.34±0.17Ba	1.79±0.63Ba	7.35±0.82Ba	0.41±0.12Aa	1.62±0.23A	4.37±0.51Aa
Backslope	CT1 *n=3*	Ap	0.84±0.18Ab	4.42±0.26Ab	14.38±6.72Ab	0.36±0.34Ab	1.17±1.46A	12.28±0.84Ab
		Bw	0.69±0.14Ab	3.63±0.13Ab	12.11±1.19Ab	0.61±0.18Ab	2.03±0.47A	5.96±0.78Ab
		Bw/C	0.46±0.04Aa	2.42±0.21Aa	6.49±2.74Aa	0.18±0,14Ab	0.48±0.37A	13.45±2.54Ab
		C	0.35±0.08Ab	1.84±0.05Ab	7.33±4.32Aa	0.17±0.13Ab	0.72±0.75A	10.83±0.82Ab
	NT *n=3*	Ap	0.69±0.03Bb	3.63±1.14Bb	11.43±1.23Bb	1.10±0.23Bb	3.46±0.56B	3.31±0.56Bb
		Bw	0.55±0.11Ba	2.89±0.78Ba	11.14±0.99Aa	0.82±0.12Bb	3.16±0.34B	3.53±0.48Bb
		Bw/C	0.21±0.14Bb	1.10±0.34Bb	3.08±0.34Bb	0.18±0,14Ab	0.48±0.37A	6.12±1.05Ba
		C	0.19±0.08Bb	1.01±0.26Bb	4.12±0.21Bb	0.18±0.13Ab	0.72±0.75A	5.62±0.87Bb
Toeslope	CT1 *N=3*	Ap	1.20±0.19Ac	6.32±0.17Ac	25.40±6.72Ac	1.03±0.34Ac	4.14±1.46A	6.14±0.84Aa
		Bw	0.59±0.13Ac	3.10±0.09Ac	10.47±1.19Aa	0.61±0.18Ab	2.06±0.47A	5.09±0.78Ab
		Bw/C	0.50±0.18Aa	2.63±0.14Aa	6.42±2.74Aa	0.42±0,14Aa	1.06±0.37A	6.27±0.54Aa
		C	0.43±0.12Ac	2.26±0.09Ac	9.45±4.32Ab	0.42±0.13Aa	1.76±0.75A	5.39±0.82Ac
	NT *n=3*	Ap	0.95±0.12Bc	5.09±1.34Bc	20.27±2.54Bc	0.96±0.23Ab	3.82±0.45A	5.31±1.12Aa
		Bw	0.79±0.09Bb	4.16±1.18Bb	15.58±1.93Bb	0.78±0.34Bc	2.92±0.61B	5.34±0.94Aa
		Bw/C	0.52±0.07Aa	2.74±0.86Aa	7.02±0.85Aa	0.42±0,14Aa	1.06±0.36A	6.53±0.61Aa
		C	0.44±0.06Ac	2.32±0.45Ac	9.81±0.91Ac	0.42±0.13Aa	1.76±0.68A	5.53±0.97Ab

Table 3. Organic matter, soil organic carbon, soil organic carbon stock, nitrogen, nitrogen stock and C:N ratio (average ± SD*) in the entire soil profile by horizons in the study area. Conventional tillage (Initial situation - September 2017), No tillage (Final situation - September 2019).SD*: Standard deviation; T-P: Topographic position; M: Management; Hor: Horizon; OM: Organic matter; SOC: Soil organic carbon; SOC-S: Soil organic carbon stock; T-SOC-S: Total soil organic carbon stock; N: Nitrogen; N-S: Nitrogen stock; T-N-S: Total nitrogen stock; C:N: Carbon nitrogen ratio. CT: Conventional tillage; NT: No tillage; n = Sample size.

Numbers followed by different capital letters are significantly different ($p < 0.05$) for the same horizon among different management (CT-NT) in the same topographical position.
Numbers followed by different lower-case letters are significantly different ($p < 0.05$) for the same horizon among different topographical position (Summit-Backslope-Toeslope) considering the same management (CT – NT).

Regarding SOC, the trend was very similar to OM patterns, ranging from 3.16 g kg^{-1} (Ap horizon-NT-CC-S) to 6.32 g kg^{-1} (Ap horizon-CT-T) on the surface, with average values for the study area of 4.31 g kg^{-1} (Ap-horizon/29.03 cm thickness) (Table 2, Table 3 and Figure 4). The SOC-S behavior was more heterogeneous than OM and SOC distribution, since the C stock depends on the gravel content, BD, SOC and the soil horizon thickness (IPCC, 2003; Stolbovoy *et al*., 2005, Stolbovoy *et al*., 2007), with average values of total SOC-S (T-SOC-S) 40.39 Mg ha^{-1} (for 125.7 cm average thickness), and varying in the Ap horizon between 8.26 Mg ha^{-1} (Ap horizon-CT-S) and 25.40 Mg ha^{-1} (Ap horizon-CT-T) (Table 3, Table 4).

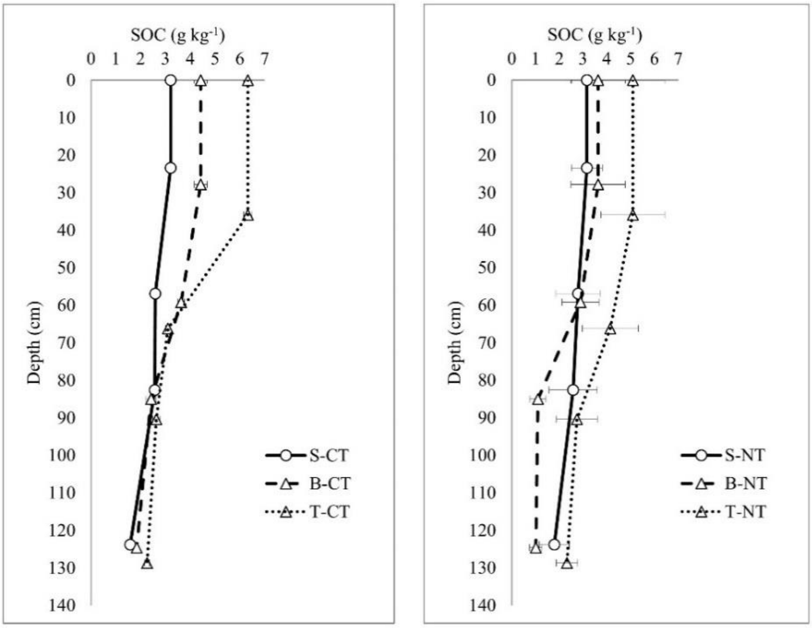


Figure 4. SOC in CT (preoperational stage) and NT (final stage) in S, B and T. NT (right side of the picture) and CT (left side of the picture). SOC: Soil organic carbon; CT: Conventional tillage; NT: No tillage; S: Summit; B: Backslope; T: Toeslope; SOC (g kg^{-1}) (average ± SD).

T-P	M	Hor	SOC-S Mg ha^{-1}	T-SOC-S Mg ha^{-1}	T-SOC-S Ap/Bw+BwC+C Mg ha^{-1}
Summit	CT1 *n=3*	Ap	8.26±6.72Aa	32.03±3.65Aa	8.26±6.72Aa
		Bw	10.72±1.19Aa		23.77±2.75Aa
		Bw/C	6.95±2.74Aa		
		C	6.10±4.32Aa		
	NT *n=3*	Ap	8.98±1.23Aa	35.78±1.23Aa	8.98±1.23Aa
		Bw	12.65±1.56Ba	CT1/NT: +11.71%	26.80±1.12Ba
		Bw/C	6.80±0.96Aa	+3.76 2y^{-1}	CT1/NT: TS/TS: +8.72%; +0.36 2y^{-1}
		C	7.35±0.82Ba		CT1/NT: SS/SS: +12.75%; +3.03 2y^{-1}
Backslope	CT1 *n=3*	Ap	14.38±6.72Ab	40.31±3.62Ab	14.38±6.72Ab
		Bw	12.11±1.19Ab		25.93±2.75Aa
		Bw/C	6.49±2.74Aa		
		C	7.33±4.32Aa		
	NT *n=3*	Ap	11.43±1.23Bb	29.77±0.96Bb	11.43±1.23Bb
		Bw	11.14±0.99Aa	CT1/NT; -26.14%	18.34±0.51Bb
		Bw/C	3.08±0.34Bb	-10.54 2y^{-1}	CT1/NT: TS/TS: -20.51%; -2.95 2y^{-1}
		C	4.12±0.21Bb		CT1/NT: SS/SS: -29.27%; -7.59 2y^{-1}
Toeslope	CT1 *N=3*	Ap	25.40±6.72Ac	51.74±3.56Ac	25.40±6.72Ac
		Bw	10.47±1.19Aa		26.34±2.75Ab
		Bw/C	6.42±2.74Aa		
		C	9.45±4.32Ab		
	NT *n=3*	Ap	20.27±2.54Bc	52.68±1.56Ac	20.27±2.54Bc
		Bw	15.58±1.93Bb	CT1/NT; +1.82%	32.41±1.23Bc
		Bw/C	7.02±0.85Aa	+0.94 2y^{-1}	CT1/NT: TS/TS: -20.19%; -5.13 2y^{-1}
		C	9.81±0.91Ac		CT1/NT: SS/SS: +23.05%; +6.07 2y^{-1}

Table 4. Soil organic carbon stock and total stock (average ± SD*) in the entire soil profile by horizons in the study area. Conventional tillage (Initial situation - September 2017), No tillage (Final situation - September 2019). SD*: Standard deviation; T-P: Topographic position; M: Management; Hor: Horizon; OM: Organic matter; SOC: Soil organic carbon; SOC-S: Soil organic carbon stock; T-SOC-S: Total soil organic carbon stock.

CT: Conventional tillage; NT: No tillage; n = Sample size. TP: Topsoil; SS: Sub soil.

Numbers followed by different capital letters are significantly different ($p < 0.05$) for the same horizon among different management (CT-NT) in the same topographical position.

Numbers followed by different lower-case letters are significantly different ($p < 0.05$) for the same horizon among different topographical position (Summit-Backslope-Toeslope) considering the same management (CT – NT).

If we compare these data with average data of OM, SOC and SOC-S at different level (Batjes, 2014; Rodríguez *et al*., 2016; Rodriguez-Murillo, 2001; Muñoz-Rojas *et al*., 2012; Castro *et al*., 2008; Zomer *et al*., 2017), we can observe the data from our study area were very low (Table 5). These differences, in some cases, may be due to differences in soil thickness between our soils and the soil references provided and in other cases they are due to soil management (CT), very aggressive with the soil (Parras-Alcántara *et al*., 2013), in fact some authors like Álvaro-Fuentes *et al*. (2011) and Rodríguez *et al*. (2016) indicate that regions like Andalusia are classified as "high erosion risk" with a mean annual soil loss of 23.2 Mg ha^{-1}, causing a significant impact on OM and SOC levels (Parras-Alcántara *et al*., 2016), affecting to SOC-S and causing decarbonization processes in the soil (Lal, 2005; Schulp *et al*., 2008).

Site	Variable	n	Th (cm)	Mg ha^{-1}	Soil type	Land use
World level[a]	SOC-S	100	0–30 cm	30	Calcic Cambisol	
		90	0–50 cm	43		
		67	0–100 cm	71		
		7	0–200 cm	115		
Europe[f]	SOC-S		0–30 cm	106		Cropland
Spain[b]	SOC-S	4401	0–30 cm	38.09		Woody crops
Spain[c]	SOC-S	45	>100 cm	39.9	Cambisol	Olive grove
		1030	>100 cm	71.4		
Andalucía[d]	SOC-S	15	0–25 cm	30.2	Cambisol	Permanent crops
			25–50 cm	18.3		
			50–75 cm	11.4		
Jaén[e]	SOC-S	35	0–15 cm	22.54		Olive grove - CT
			0–30 cm	38.99		

Table 5. Soil organic carbon stock at different level. n: sample size; Th: Thickness; SOC-S: Soil organic carbon stock. [a] Batjes (2014); [b] Rodríguez *et al*. (2016), considering 30 cm in the topsoil layer according to the Eurostat guidelines in EU

programmes. [c] Rodriguez-Murillo (2001). [d] Muñoz-Rojas *et al*. (2012). [e] Castro *et al*. (2008). [f] Zomer *et al*. (2017).

4.3.3.3. Effects of conventional tillage on SOC, total N and C:N in the hillsides, baseline situation.

The baseline research situation as previously stated (CT - September 2017), indicates that these soils are characterized by low OM content (Ap horizon: 0.88% on average) (Table 3), this leads low aggregates stability, high erosion rates and therefore low agricultural productivity (*Cerdà et al*., 2010). Furthermore, long-term OM decomposition in Mediterranean permanent woody-crops soils such as traditional OG causes soil degradation, reducing a sustainable production (Hemmat *et al*., 2010). Not forgetting that intensive management - CT in Mediterranean soils causes land degradation by SOM depletion and erosion (Morugán-Coronado *et al*., 2020).

The main characteristic of the studied soils was a reduction in the SOC concentrations in depth in the three topographical positions (S: Ap horizon 3.2 g kg^{-1} – C horizon 1.6 g kg^{-1}; B: Ap horizon 4.4 g kg^{-1} – C horizon 1.8 g kg^{-1}; T: Ap horizon 6.3 g kg^{-1} – C horizon 2.3 g kg^{-1}). Similar results have been obtained by Castro *et al*. (2008), Parras-Alcántara *et al*. (2013) and Hernanz *et al*. (2009) among others, justifying these results by the semiarid Mediterranean conditions, by the high OM mineralization and by the lack of crop residues after periods of drought. Other important issue was the SOC increase along hillside (from the highest positions (S-position) to the lowest positions (T-position), with significant differences ($p < 0.05$) on the surface horizon, where SOC doubled its concentration in T with respect to S position (S: Ap horizon 3.2 g kg^{-1}; T: Ap horizon 6.3 g kg^{-1}) (Table 3). This increase on SOC concentration along the hillside was due to water erosion processes. In this sense, Martínez-Mena *et al*. (2008), have linked the SOC loss with erosion, especially in semi-arid areas. Furthermore, CT with intensive tillage, contributes to soil loss through water erosion (Rodríguez-Lizana *et al*., 2008) accelerating the OM decomposition rates and causing the structural aggregates breakdown in the soil (*Paustian et al*., 2000).

Regarding nitrogen (N) concentrations, in general terms, the trend was similar to SOC concentrations, decreasing in depth except for Bw horizon-CT-S and for Bw horizon-CT-B (Table 3) in the first case it decreased with respect to the lower horizons (Bw horizon 0.30 g kg^{-1} - Bw/C horizon 0.42 g kg^{-1}) and in the second case it increased with respect to the upper horizons (Ap horizon 0.36 g kg^{-1} - Bw horizon 0.61 g kg^{-1}). But it is important to point out that the main differences occurred on the surface (Ap - Bw horizons) in all topographic position and throughout the entire soil profile in B position (Table 3). This N behavior in soil surface could be caused by soil erosion and N alteration in the superficial horizons influenced by the urea leaching (nitrogen-based fertilizer), and the lack of vegetation cover (Sanz-Cobena *et al*., 2012).

With respect to C:N ratio the values were low, ranging from 3.77 (C horizon-CT-S) to 13.45 (Bw/C horizon-CT-B) along the profile, highlighting low surface values, except for Ap horizon-CT-B (12.28).

The C:N ratio showed a no clear pattern in depth, however, it has been shown that high BD is associated with highly OM decomposed, with lower C:N ratios (Brevik *et al*., 2002), this could explain the differences in the C:N ratios found in the study soils. However, high C:N ratio (>12) values indicate lack of N in the soil (Batjes and Dijkshoorn, 1999), other studies indicate that high clay contents are associated with more OM decomposed and lower C:N ratios (Puget and Lal, 2005; Yamashita *et al*., 2006). In CT, the residues entrance is very limited, except for the Ap horizon. Therefore, in the study soils, the C:N ratio can be stratified showing a general decreasing in depth. The surface C:N ratio was slightly higher compared to the deeper horizons, indicating high resolution and separation rates. In this line, Lal *et al*. (1995) indicated that C:N ratios are low during resolution and separation times.

4.3.3.4. Effects of no tillage on SOC, total N and C:N in the hillside, final stage research.

LMC in short-term (NT -CC- final stage - September 2019) with respect to SOC content, showed a greater homogenization of the data, producing a SOC content reduction in depth in all topographic positions. In this context, it is important to clarify that SOC concentrations are determined by the balance between the new C inputs and the old SOM decomposition, due to the LMC duration and the soil depth (*Kumar et al*., 2019). This SOC reduction in depth can be attributed to the high gravel and BD contents of these soil layers (Table 2), restricting physically that the roots from reaching deeper layers (Francaviglia *et al*., 2017). Furthermore, Parras-Alcántara *et al*. (2013) justified low SOC concentration in depth due to SOC stratification since the entry of residues is restricted to the soil surface layer. In this sense, Jobbágy and Jackson (2000) indicated that climatic conditions and clay content can condition the SOC amount, which corroborates the results obtained in this study. And since SOM is superficially concentrated, the C mineralization and immobilization mechanisms are more active in topsoil layer (Hiederer, 2009). In this line, it is important to highlight that in depth (Bw/C - C horizons) no significant differences ($p < 0.05$) were found with respect to SOC along the hillside, except for B (intermediate position). Similar results regarding to SOC in depth were found by Parras-Alcántara and Lozano-García (2014) in CM with LMC (from CT to organic farming) for 20 years, arguing that organic farming had little influence on SOC in Mediterranean dehesa so that in Mediterranean areas are necessary more years (>20 years) to find changes in depth. However, the SOC reduction in depth (CT: Bw/C horizon - 2.42 g kg^{-1}, C horizon - 1.84 g kg^{-1}; NT-CC: Bw/C horizon - 1.10 g kg^{-1}, C horizon - 1.01 g kg^{-1}) in B topographic position due to the LMC (CT to NT-CC) could be due to a high OM decomposition rate due to changes in temperature and humidity regime in depth. In this respect, Cenkseven *et al*. (2017) in Mediterranean areas (Turkey) argued that, the plant type, the soil depth, the temperature and the humidity of the soil affect to C and N mineralization, and that the sensitivity to the temperature in the mineralization processes is observed from 32 °C in the top soil, while than from 24 °C in the deepest soil layer, potentially increasing the C and N mineralization as the temperature increased. Also, is important to note that for concave topographies the soil temperature increased (*Sierra et al.*, 2011).

With respect to the surface horizons (Ap and Bw horizons), no significant differences ($p < 0.05$) were found in the SOC content due to LMC (Table 3 and Figure 4). However, we observed a SOC reduction in surface (Ap horizon), and a SOC increase in the Bw horizon due to the LMC (S-CT: Ap horizon 3.21 g kg^{-1}, Bw horizon 2.59 g kg^{-1}/S-NT-CC: Ap horizon 3.16 g kg^{-1}, Bw horizon 2.79 g kg^{-1}; B-CT: Ap horizon 4.42 g kg^{-1}, Bw horizon 3.63 g kg^{-1}/B-NT-CC: Ap horizon 3.63 g kg^{-1}, Bw horizon 2.89 g kg^{-1}; T-CT: Ap horizon 6.32 g kg^{-1}, Bw horizon 3.10 g kg^{-1}/T-NT-CC: Ap horizon 5.09 g kg^{-1}, Bw horizon 4.16 g kg^{-1}) (Table 3). This SOC increase in NT-CC in Bw horizon in short-term (2 year) due to LMC could be explained by the soil texture and by management, since the SOC concentration can be reduced in the soil surface due to soluble organic compounds that can filter in depth, increasing the soil aggregates (Diekow *et al.*, 2005). However, other authors (González *et al.*, 2012) point out, that the SOC is favored by large OM inputs, high soil clay contents, a calcium saturated soil matrix. Therefore, in the studied soil the SOC increased the C inputs by increase of the crop biomass and hence residues return, as a result OM in deeper horizon increased too.

The N concentrations varied between 0.18 g kg^{-1} (Bw/C horizon-CT-B) and 1.10 g kg^{-1} (Ap horizon-NT-CC-B), showing similar trend that SOC, highlighting that there are no significant differences ($p < 0.05$) in depth with respect to management, and that the N concentrations generally decreased in depth increasing down the slope ($S < B < T$ topographic positions). It is important to highlight the increase in N concentrations in the Bw horizon due to the LMC, varying between 76.7%, 34.4% and 27.9% for S, B and T positions, respectively (Figure 5).

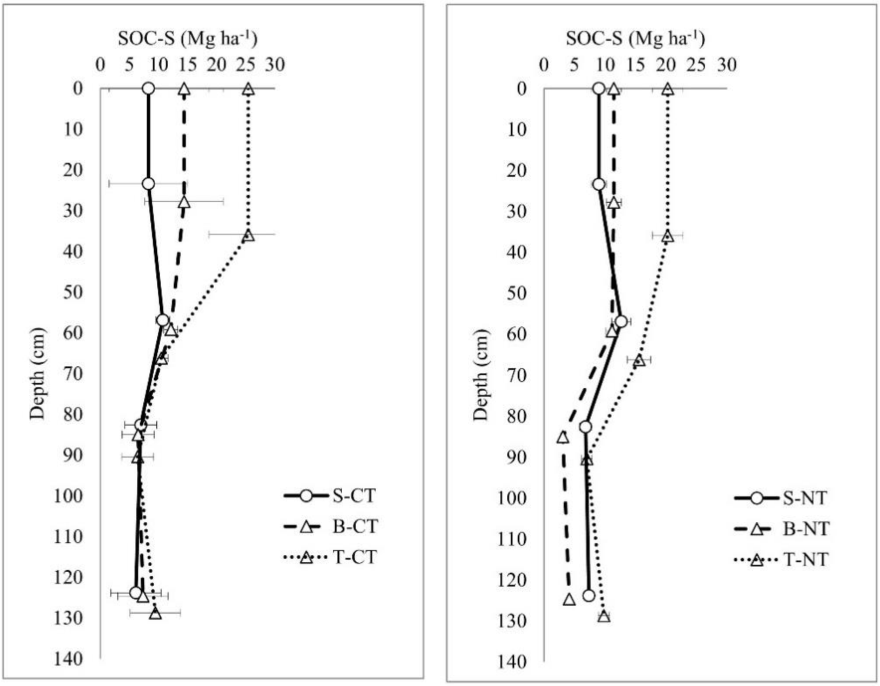


Figure 5. SOC-S in CT (preoperational stage) and NT (final stage) in S, B and T. NT (right side of the picture) and CT (left side of the picture). SOC-S: Soil organic carbon stock; CT: Conventional tillage; NT: No tillage; S: Summit; B: Backslope; T: Toeslope; SOC ($g\ kg^{-1}$) (average ± SD).

The C:N ratios were highly variable, ranging between 4.37 (C horizon-NT-CC-S) and 13.45 (Bw/C horizon-CT-B) finding few significant differences ($p < 0.05$) in depth, this indicates low resolution and separation rates. In this sense, Sá *et al.*, 2001 observed an increase in the C:N ratio with depth, which can be attributed to some soluble organic compounds that filter into deeper layers, increasing the C:N ratio in depth (Diekow *et al*., 2005), as it happens in some of the studied soils (B horizon-CT) (Table 3).

4.3.3.5. Effects of land management change on SOC-S.

LMC effects (CT to NT-CC) on SOC-S in OG hillside in 2 years (short time), could be simplified in: (i) SOC-S reduction in depth, (ii) SOC-S increase in the Bw horizon with respect to the Ap horizon in the upper topographic position (S), (iii) an increase in the total SOC-S (T-SOC-S) due to the LMC except for the intermediate topographic position (B) and (iv) an increase in the SOC-S along the slope (from the highest topographic positions to the lowest) (Table 3, Table 4).

(i) *SOC-S reduction in depth*: The general trend was a reduction on SOC-S in depth, both in CT and in NT-CC. Ranging from 20.27 Mg ha^{-1} to 3.08 Mg ha^{-1} for Ap horizon-NT-CC-T and Bw/C horizon-NT-CC-B respectively. In agreement with Kumar *et al*. (2019), Francaviglia *et al*. (2017), Parras-Alcántara *et al*. (2013) and Jobbágy and Jackson (2000), the SOC-S concentrations are conditioned by the balance between C inputs to the soil and the SOM decomposition, to the gravel content and BD variations that restricting physically that the roots from reaching deeper layers, to the SOC-S stratification since the residues entry is restricted to the soil surface and to the climatic conditions and to the clays content respectively. Despite this reduction in depth, it is important to highlight the high concentration of SOC-S in depth for the most depressed topographic position (C horizon-CT-T 9.45 Mg ha^{-1} and C horizon-NT-CC-T 9.81 Mg ha^{-1}), which must be taken into account to avoid a underestimation to T-SOC-S, due mainly to BD difference (Bateni *et al*., 2017).

(ii) *SOC-S increase in the Bw horizon with respect to the Ap horizon in the upper topographic position (S)*: The SOC-S decreased in depth in all cases (CT and NT-CC) except for the upper topographic position (S) where SOC-S concentrations decreased in Ap horizon (S-CT: Ap 8.26 Mg ha^{-1}, Bw 10.72 Mg ha^{-1}; S-NT-CC: Ap 8.98 Mg ha^{-1}, Bw 12.65 Mg ha^{-1}). This truncation-alteration in the SOC-S in this topographic position (S), may be due to water erosion increase, linked to a slightly steeper slope than the rest of the hillside. In this sense, Parras-Alcántara *et al*. (2016), in these same soils with CT on slopes of 5%, applying the RUSLE model obtained average soil losses of 6.60 Mg ha^{-1} yr^{-1} using quadratic equations with very high correlations ($R^2 = 0.9911$). This fact has also been corroborated by Lozano-García *et al*. (2011) using LUW minisimulator in these soils with slopes of 4%, obtaining very high soil losses (55.06 ± 1.3 Mg ha^{-1} h^{-1}). However, it is important to note that the LMC from CT to NT-CC for two years, in S position increased the SOC-S concentration by 8.7% and 18% for Ap and Bw horizons respectively, linked to an increase in OM and clay content and reduction in the gravel content (Table 2, Table 3). Thus, Francia Martínez *et al*. (2006) and García *et al*.

(2006) showed that soil management alters soil erodibility - susceptibility to water erosion in OG, especially in semi-arid areas, therefore, we can say that NT-CC reduced water erosion.

(iii) *an increase in the total SOC-S (T-SOC-S) due to the LMC except for the intermediate topographic position (B)*: The T-SOC-S analysis along the hillside due to LMC in two years, showed an increase in the T-SOC-S in S (+11.71%) and T (+1.82%) topographic positions, however in B topographic position it decreased (−26.14%) (Table 4). This increase on SOC-S can be attributed to LMC (less aggressive) and the spontaneous cover crops presence. In this sense, Haynes and Francis (1993) indicated that herbaceous enrich the soil with labile organic substances through rhizodeposition processes and the activity of root-associated microorganisms. In addition, there is an additional soil enrichment with fresh OM from this spontaneous vegetation (Brunetto *et al*., 2011). Without forgetting that the waste decomposition derived from pruning that would mean another extra contribution from SOM (Massaccesi *et al*., 2018).

With respect to the intermediate topographic position (B), the T-SOC-S is significantly reduced (CT-B 40.31 Mg ha^{-1}, NT-CC-B 29.77 Mg ha^{-1}) (Table 4). This 10.54% reduction in T-SOC-S could be the result of very intense erosive processes (Gollany and Elnaggar, 2017) derived from LMC. In this sense, Gómez *et al*. (2009), indicated that NT-CC could affect negatively to soil conservation compared to CT, due to a decrease in OM, macroaggregates, infiltration rates and increased of soil consolidation with NT-CC compared to CT in short term.

Although we must not forget that the observation scale influences the SOC-S quantification (Wiesmeier *et al*., 2019), therefore, local terrain attributes (slope, aspect and curvature) influence on SOC-S at small spatial scales (<100 m) and the topographic position is important at larger scales (>100 m) (Hobley *et al*., 2016), so that, the topography is relevant at the local scale (hillsides) where the soil properties do not vary much, however, they are less relevant in larger areas, where the SOC-S is averaged over a wide variety of soil properties for that other factors become dominant.

(iv) *an increase in the SOC-S along the slope (from the highest topographic positions to the lowest)*: The SOC-S increased from the highest topographic position (S) to the lowest parts (T), ranging from 35.78 Mg ha^{-1} in S position to 52.58 Mg ha^{-1} in T. Other authors such as Lozano-García and Parras-Alcántara (2014) in CM have obtained similar results in toposequences of traditional Mediterranean OG, arguing an increase in particles and OM in hillsides lower parts due to water erosion. Others, such as Martínez-Mena et al. (2008) have highlighted the erosion contribution in the SOC loss, especially in semi-arid areas. In this context, CT contributes considerably to soil loss through erosion (Rodríguez-Lizana et al., 2008) and accelerates the OM decomposition as a result of the soil aggregates destruction

(Balesdent et al., 2000). Furthermore, this effect on SOC loss increases with the years of cultivation (Gregorich et al., 1998).

From the results above, we can affirm that two different mechanisms due to LMC have occurred in two years: carbonization (S and T position) and decarbonization (B position) (Table 4). In the first case (carbonization), the increase on SOC-S was 1.88 Mg ha^{-1} y^{-1} and 0.47 Mg ha^{-1} y^{-1} for S and T topographic position respectively, however the decarbonization in topographic position B was 5.27 Mg ha^{-1} y^{-1}. The tillage absence in NT-CC improves the soil microbial and fauna communities and the formation of stable aggregates (Jégou *et al*., 2000), providing protection against to OM decomposition (Del Galdo *et al*., 2003). Therefore, Mediterranean soils have a great capacity to C store and C sequestration - C sink (Roig and Rubio, 2009). In addition, permanent crops such vineyards, OG, nuts and almonds in Mediterranean areas contribute to 3% of the T-SOC-S (Gómez, 2017).

4.3.4. Conclusions.

LMC from CT to NT-CC with application of pruned olive branch chippings branches and vegetation cover (spontaneous vegetation) in the streets in Mediterranean OG hillsides for short-term (two years) showed that: (i) in two years, the soil physical properties due to LMC did not change significantly along to hillsides, (ii) CT (very intensified) has caused land degradation over time due to strong water erosion, affecting to OM and SOC contents, resulting soil decarbonization, (iii) LMC involved a SOC reduction in top soil (Ap horizon) and a SOC increase in the Bw horizon due to slight textural changes in the soil (clay content) and management (SOC is reduced in surface due to soluble organic compounds that can filter in depth), (iv) in general the T-SOC-S due to the LMC except for the intermediate topographic position increased the SOC-S content from the highest topographic positions to the lowest and (v) two years with NT-CC showed soil carbonization (S and T position) and decarbonization (B position) processes.

Therefore, LMC has a positive effect on SOC reserves in S and T position, however in B position, this effect was negative. In addition, to indicate that in certain parts of the world, under certain climatic characteristics (Mediterranean areas) the soil regeneration is possible. This study demonstrates the importance of SOC-S assessment after LMC for a proper management planning in Mediterranean areas.

4.3.5. References.

AEMA - Agencia Europea del Medio Ambiente, 2015. El suelo y el cambio climático. http://www.eea.europa.eu/es/senales/senales-2015/articulos/el-suelo-y-el-cambio-climatico.

AEMET - Agencia Estatal de Meteorología, 2020. Standard climate values - Period: 1983-2010. Last accessed (16/03/2020). http://www.aemet.es/en/serviciosclimaticos/datosclimatologicos/valoresclimatologicos?l=5270B&k=and

Alcaide, R., 2013. Estudio de suelos sobre olitostromas en la campiña de Torredelcampo, Jaén. Tesis de Licenciatura, Universidad de Córdoba. Inédita.

Al-Kaisi, M.M., Yin, X., Licht, M.A., 2005. Soil carbon and nitrogen changes as influenced by tillage and cropping systems in some Iowa soils. Agric. Ecosyst. Environ. 105, 635-647. https://dx.doi.org/10.1016/j.agee.2004.08.002.

Álvaro-Fuentes, J., Easter, M., Cantero-Martínez, C., Paustian, K., 2011. Modelling soil organic carbon stocks and their changes in the northeast of Spain. Eur. J. Soil Sci. 62, 685-695. https://dx.doi.org/10.1111/j.1365-2389.2011.01390.x.

Álvaro-Fuentes, J., Lóczy, D., Thiele-Bruhn, S., Zornoza, R., 2019. Handbook of plant and soil analysis for agricultural systems. Cartagena – Spain: Crai uptc Editions, 389 pp. http://doi.org/10.5281/zenodo.2553445.

Avilés-Hernández, V., Velázquez-Martínez, A., Ángeles-Pérez, G., Etchevers-Barra, J., De los Santos-Posadas, H., Llandera, T., 2009. Variación en almacenes de carbono en suelos de una toposecuencia. Agrociencia 43, 457-464.

Balesdent, J., Chenu, C., Balabane, M., 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res. 53, 215-230. https://dx.doi.org/10.1016/S0167-1987(99)00107-5.

Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute (Eds). Methods of soil analysis, Part 1: Physical and Mineralogical methods. 2nd Ed. ASA, SSSA. Madison, WI, pp. 377-382.

Bateni, C., Ventura, M., Tonon, G., Pisanelli, A., 2017. Soil carbon stock in olive groves agroforestry systems under different management and soil characteristics. Agrofor. Syst. https://dx.doi.org/10.1007/s10457-019-00367-7.

Batjes, N.H., Dijkshoorn, J.A., 1999. Carbon and nitrogen stocks in the soils of Amazon Region. Geoderma 89, 273-286. https://dx.doi.org/10.1016/S0016-7061(98)00086-X.

Batjes, N.H., 2014. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci. 65, 10-25. https://dx.doi.org/10.1111/ejss.12114_2.

Bochet, E., 2015. The fate of seeds in the soil: a review of the influence of overland flow on seed removal and its consequences for the vegetation of arid and semiarid patchy ecosystems. Soil 1, 131-146. https://dx.doi.org/10.5194/soil-1-131-2015.

Bremner, J.M., 1996. Total nitrogen. In: Sparks, D.L. (Ed.), Methods of Soil Analysis. Part 3. Chemical Methods. SSSA Book Series No 5. Soil Science Society of America, Madison, WI, pp. 1085–1086.

Brevik, E.C., Fenton, T.E., Moran, L.P., 2002. Effect of soil compaction on organic carbon amounts and distribution, south-central Iowa. Environ. Pollut. 116, S137-S141. https://dx.doi.org/10.1016/S0269-7491(01)00266-4.

Brunetto, G., Ventura, M., Scandellari, F., Ceretta, C.A., Kaminski, J., Wellington de Melo, G., et al. 2011. Nutrient release during the decomposition of mowed perennial ryegrass and white clover and its contribution to nitrogen nutrition of grapevine. Nutr. Cycl. Agroecosyst. 90, 299-308. https://dx.doi.org/10.1007/s10705-011-9430-8.

Castro, J., Fernández-Ondono, E., Rodríguez, C., Lallena, A.M., Sierra, M., Aguilar, J., 2008. Effects of different olive-grove management systems on the organic carbon and nitrogen content of the soil in Jaen (Spain). Soil Till. Res. 98, 56-67. https://dx.doi.org/10.1016/j.still.2007.10.002.

Caviglia, O.P., Wingeyer, A.B., Novelli, L. E., 2016. El rol de los suelos agrícolas frente al cambio climático. Serie de Extensión INTA Paraná. 78, 27-32.

Cenkseven, S., Kizildag, N., Kocak, B., Sagliker, A., Darici, C., 2017. Soil organic matter mineralization under different temperatures and moisture conditions in Kızıldağ plateau, Turkey. Sains Malays. 46(5), 763-771. http://dx.doi.org/10.17576/jsm-2017-4605-11.

Cerdá, A., 2001. Effects of rock fragment cover on soil infiltration, interrill runoff and erosion. Eur. J. Soil Sci. 52, 59-68. https://dx.doi.org/10.1046/j.1365-2389.2001.00354.x.
Cerdà, A., Lavee, H., Romero-Díaz, A., Hooke, J., Montanarella, L., 2010. Soil erosion and degradation on Mediterranean type ecosystems. Land Degrad. Dev. 21, 71-74. https://dx.doi.org/10.1002/ldr.968.
Conforti, M., Longobucco, T., Scarciglia, F., Niceforo, G., Matteucci, G., Buttafuoco, G., 2020. Interplay between soil formation and geomorphic processes along a soil catena in a Mediterranean mountain landscape: an integrated pedological and geophysical approach. Environ. Earth Sci. 79, 59. https://dx.doi.org/10.1007/s12665-019-8802-2.
Costa, C., Papatheodorou, E.M., Monokrousos, N., Stamou, G.P., 2015. Spatial variability of soil organic C, inorganic N and extractable P in a Mediterranean grazed area. Land Degrad. Dev. 26, 103-109. https://dx.doi.org/10.1002/ldr.2188.
Cowling, R.M., Ojeda, F., Lamont, B., Rundel, P.W., Lechmere-Oertel, R., 2005. Rainfall reliability, a neglected factor in explaining convergence and divergence of plant traits in fire-prone Mediterranean-climate ecosystems. Global Ecol. Biogeogr. 14, 509-519. https://dx.doi.org/10.1111/j.1466-822X.2005.00166.x.
De Alba, S., Lindstrom, M., Schumacher, T. E., Maloc, D. D., 2004. Soil landscape evolution due to soil redistribution by tillage: A new conceptual model of soil catena evolution in agricultural landscapes. Catena 58(1), 77-100. https://dx.doi.org/10.1016/j.catena.2003.12.004.
De la Rosa, D., Moreira, J.M., 1987. Evaluación agroecológica de recursos naturales de Andalucía. Sevilla, Spain: Agencia de Medio Ambiente, Junta de Andalucía.
Del Galdo, I., Six, J., Peressotti, A., Cotrufo, M.F., 2003. Assessing the impact of land use change on soil C sequestration in agricultural soils by means of organic matter fractionation and stable C isotopes. Glob. Change Biol. 9, 1204-1213. https://dx.doi.org/10.1046/j.1365-2486.2003.00657.x.
Diekow, J., Mielniczuk, J., Knicker, H., Bayer, C., Dick, D.P., Kögel-Knabner, I., 2005. Soil C and N stocks as affected by cropping systems and nitrogen fertilisation in a southern Brazil acrisol managed under no-tillage for 17 years. Soil Tillage Res. 81, 87-95. https://dx.doi.org/10.1016/j.still.2004.05.003.
Eaton, J.M., McGoff, N.M., Byrne, K.A., Leahy, P., Kiely, G., 2008. Land cover change and soil organic C stocks in the Republic of Ireland 1851-2000. Clim. Change 91, 317-334. https://dx.doi.org/10.1007/s10584-008-9412-2.
E.C., 2006. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee of the Regions. Thematic Strategy for Soil Protection, Brussels. COM (2006) 231 final.
E.C., 2011. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Roadmap to a resource Efficient Europe. Official Journal of the European Union, Brussels. COM (2011) 571 final.
E.C., 2012. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions,

The implementation of the Soil Thematic Strategy and ongoing activities. Official Journal of the European Union, Brussels. COM (2012) 46 final.

Fernández-Romero, M.L., Lozano-García, B., Parras-Alcántara, L., 2014. Topography and land use change effects on the soil organic carbon stock of forest soils in Mediterranean natural areas. Agric. Ecosyst. Environ. 195, 1-9. https://dx.doi.org/10.1016/j.agee.2014.05.015.

Fernández-Romero, M.L., Parras-Alcántara, L., Lozano-García, B., Clark, J.M., Collins, C.D., 2016a. Soil quality assessment based on carbon stratification index in different olive grove management practices in Mediterranean areas. Catena 137, 449-458. http://dx.doi.org/10.1016/j.catena.2015.10.019.

Fernández-Romero, M.L., Lozano-García, B., Parras-Alcántara, L., Collins, C.D., Clark, J.M., 2016b. Effects of land management on different forms of soil carbon in olive groves in Mediterranean areas. Land Degrad. Dev. 27, 1186-1195. https://dx.doi.org/10.1002/ldr.2327.

Francaviglia, R., Renzi, G., Doro, L., Parras-Alcántara, L., Lozano-García, B., Ledda, L., 2017. Soil sampling approaches in Mediterranean agro-ecosystems. Influence on soil organic carbon stocks. Catena, 158, 113-120. http://dx.doi.org/10.1016/j.catena.2017.06.014.

Francaviglia, R., Ledda, L., Farina, R., 2018. Organic carbon and ecosystem services in agricultural soils of the Mediterranean Basin. In Sustainable Agriculture Reviews 28; Gaba, S., Smith, B., Lichtfouse, E., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 183–210.

Francia Martínez, J.R., Durán Zuazo, V.H., Martínez Raya, A., 2006. Environmental impact from mountainous olive orchard under different soil-management system (SE Spain). Sci. Total Environ. 358, 46-60. https://dx.doi.org/10.1016/j.scitotenv.2005.05.036.

Gallardo, A., Rodríguez-Saucedo, J., Covelo, F., Fernández-Ales, R., 2000. Soil Nitrogen heterogeneity in dehesa ecosystem. Plant Soil 222, 71-82. https://dx.doi.org/10.1023/A:1004725927358.

García, J.A., Battany, M., Renschler, C.S., Fereres, E., 2006. Evaluating the impact of soil management on soil loss in olive orchards. Soil Use Manage. 19(2), 127-134. https://dx.doi.org/10.1111/j.1475-2743.2003.tb00292.x.

García-Orenes, F., Roldán, A., Mataix-Solera, J., Cerdà, A., Campoy, M., Arcenegui, V., Caravaca, F., 2012. Soil structural stability and erosion rates influenced by agricultural management practices in a semi-arid Mediterranean agro-ecosystem. Soil Use Manag. 28, 571-579. http://dx.doi.org/10.1111/j.1475-2743.2012.00451.x.

Ghosh, P.K., Hazra, K.K., Nath, C.P., 2018. Soil carbon management through crop diversification and sustainable intensification. XXI Biennial National Symposium of Indian Society of Agronomy, 24–26 October 2018 at MPUAT, Udaipur, Rajasthan.

Gollany, H.T., Elnaggar, A.A., 2017. Simulating soil organic carbon changes across toposequences under dryland agriculture using CQESTR. Ecol. Model. 355, 97-104. https://dx.doi.org/10.1016/j.ecolmodel.2017.03.024.

Gómez, J.A., 2017. Sustainability using cover crops in Mediterranean tree crops, olives and vines – Challenges and current knowledge. Hung. Geogr. Bull. 66, 13-28. https://dx.doi.org/10.15201/hungeobull.66.1.2.

Gómez, J.A., Sobrinho, T.A., Giráldez, J.V., Fereres, E., 2009. Soil management effects on runoff, erosion and soil properties in an olive grove of Southern Spain. Soil Tillage Res. 102, 5-13. https://dx.doi.org/10.1016/j.still.2008.05.005.

González, I., Grau, J.M., Fernández, A., Jiménez, R., González, M.R., 2012. Soil carbon stocks and soil solution chemistry in Quercus ilex stands in Mainland Spain. Eur. J. For. Res. 131, 1653-1667. https://dx.doi.org/10.1007/s10342-012-0623-8.

Gregorich, E.G., Greer, K.J., Anderson, D.W., Liang, BC., 1998. Carbon distribution and losses: erosion and deposition effects. Soil Tillage Res. 47, 291-302. https://dx.doi.org/10.1016/S0167-1987(98)00117-2.

Griffiths, R.P., Madritch, M.D., Swanson, A.K., 2009. The effects of topography on forest soil characteristics in the Oregon Cascade mountains (USA): implications for the effects of climate change on soil properties. For. Ecol. Manag. 257, 1-7. https://dx.doi.org/10.1016/j.foreco.2008.08.010.

Guitián, F., Carballas, T., 1976. Técnicas de Análisis de Suelos. Picro Sacro, Santiago de Compostela.

Haynes, R.J., Francis, G.S., 1993. Changes in microbial biomass C, soil carbohydrate composition and aggregate stability induced by growth of selected crop and forage species under field conditions. J. Soil Sci. 44, 665-675. https://dx.doi.org/10.1111/j.1365-2389.1993.tb02331.x.

Hemmat, A., Aghilinategh, N., Rezainejad, Y., Dadeghi, M., 2010. Long-term impacts of municipal solid waste compost, sewage sludge and farmyard manure application on organic carbon, bulk density and consistency limits of a calcareous soil in central Iran. Soil Tillage Res. 108, 43-50. https://dx.doi.org/10.1016/j.still.2010.03.007.

Hernanz, J. L., Sanchez-Giron, V., Navarrete, L., 2009. Soil carbon sequestration and stratification in a cereal/leguminous crop rotation with three tillage systems in semiarid conditions. Agric. Ecosyst. Environ. 133, 114-122. https://dx.doi.org/10.1016/j.agee.2009.05.009.

Hiederer, R., 2009. Distribution of Organic Carbon in Soil Profile Data. EUR 23980 EN. Office for Official Publications of the European Communities, Luxembourg, pp. 126.

Hobley, E.U., Baldock, J., Wilson, B., 2016. Environmental and human influences on organic carbon fractions down the soil profile. Agric. Ecosyst. Environ. 223, 152-166. https://dx.doi.org/10.1016/j.agee.2016.03.004.

Intergovernmental Panel on Climate Change (IPCC), 2003. In: Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F., (Eds.), Good Practice Guidance for Land Use, Land Use Change and Forestry. IPCC/OECD/IEA/IGES, Hayama, Japan.

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Jégou, D., Cluzeau, D., Hallaire, V., Balesdent, J., Tréhen, P., 2000. Burrowing activity of the earthworms Lumbricus terrestris and Aporrectodea giardi and consequences on C transfers in soil. Eur. J. Soil Biol. 36, 27-34. https://dx.doi.org/10.1016/S1164-5563(00)01046-3.

Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol. Appl. 10, 423-436. http://dx.doi.org/10.2307/2641104.

Jordán, A., Zavala, L.M., Gil, J., 2010. Effects of mulching on soil physical properties and runoff under semi-arid conditions. Catena 81, 77-85. https://dx.doi.org/10.1016/j.catena.2010.01.007.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated. Meteorol. Zeitschrift 15(3), 259-263. http://dx.doi.org/10.1127/0941-2948/2006/0130.

Kumar, R., Naresh, R.K., Kumar, R., Tomar, S.K., Kumar, A., Chandra, M.S., Singh, O., Mahajan, N.C., Kumar, R., 2019. Conservation Tillage Impact on Topsoil and Deep Soil Aggregation and Aggregate Associated Carbon Fractions and Microbial Community Composition in Subtropical India: A Review. Int. J. Curr. Microbiol. App. Sci. 8(10), 283-302. https://dx.doi.org/10.20546/ijcmas.2019.810.030.

Lal, R., 2005. Forest soils and carbon sequestration. Forest Ecol. Manag. 220(1-3), 242-258. https://dx.doi.org/10.1016/j.foreco.2005.08.015.

Lal, R. 2010. Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. Bioscience 60, 708-721. https://dx.doi.org/10.1525/bio.2010.60.9.8.

Lal, R., 2016. Beyond COP 21: potential and challenges of the "4 per Thousand" initiative. J. Soil Water Conserv. 71, 20A-25A. http://dx.doi.org/10.2489/jswc.71.1.20A.

Lal, R., Kimble, J., and Stewart, B. A., 1995. World Soils as a or sink for radio-active gases, in: Soil management and greenhouse effect, edited by: Jorgensen, B. B., Lewis, London, 1-7.

López-Piñeiro, A., Albarrán, A., Rato, J.M., Peña, D., Cabrera, D., 2011. Long-term impacts of de-oiled two-phase olive mill waste on soil chemical properties, enzyme activities and productivity in an olive grove. Soil Tillage Res. 114, 175-182. https://dx.doi.org/10.1016/j.still.2011.05.002.

Lozano-García, B., Parras-Alcántara, L., del Toro Carrillo de Albornoz, M., 2011. Effects of oil mill wastes on surface soil properties, runoff and soil losses in traditional olive groves in southern Spain. Catena 85, 187-193. http://dx.doi.org/10.1016/j.catena.2011.01.017.

Lozano-García, B., Parras-Alcántara, L., 2014. Variation in soil organic carbon and nitrogen stocks along a toposequence in a traditional Mediterranean olive grove. Land Degrad. Dev. 25, 297-304. https://dx.doi.org/10.1002/ldr.2284.

Lozano-García, B., Muñoz-Rojas, M., Parras-Alcántara, L., 2017. Climate and land use changes effects on soil organic carbon stocks in a Mediterranean semi-natural area. Science of the Total Environment, 579; 1249–1259. http://dx.doi.org/10.1016/j.scitotenv.2016.11.111.

Lugato, E., Panagos, P., Bampa, F., Jones, A., Montanarella, L., 2014. A new baseline of organic carbon stock in European agricultural soils using a modelling approach. Glob. Change Biol. 20, 313-326. https://dx.doi.org/10.1111/gcb.12292.

Martínez-Mena, M., López, J., Almagro, M., Boix-Fayos, C., Albadalejo, J., 2008. Effect of water erosion and cultivation on the soil carbon stock in a semiarid area of South-East Spain. Soil Till. Res. 99, 119-129. https://dx.doi.org/10.1016/j.still.2008.01.009.

Massaccesi, L., De Feudis, M., Nasini, L., Regni, L., D'Ascoli, R., Castaldi, S., Proietti, P., Agnelli, A., 2018. Organic carbon pools and storage in the soil of olive groves of different age. Eur. J. Soil Sci. 69(5). https://dx.doi.org/10.1111/ejss.12677.

McDonough W., 2016. Carbon is not the enemy. Nature 539, 349-351.

Milgroom, J., Garrido, J.M., Gómez, J.A., Fereres, E., 2007. The influence of a shift from conventional to organic olive farming on soil management and erosion risk in southern Spain. Renew. Agr. Food Syst. 22, 1-10. https://dx.doi.org/10.1017/S1742170507001500.

Morugán-Coronado, A., Linares, C., Gómez-López, M.D., Faz, Á., Zornoza, R., 2020. The impact of intercropping, tillage and fertilizer type on soil and crop yield in fruit orchards under Mediterranean conditions: A meta-analysis of field studies. Agric. Syst. 178, 102736. https://dx.doi.org/10.1016/j.agsy.2019.102736.

Moscatelli, M.C., Di Tizio, A., Marinari, S., Grego, S., 2007. Microbial indicators related to soil carbon in Mediterranean land use systems. Soil Till. Res. 97, 51-59. https://dx.doi.org/10.1016/j.still.2007.08.007.

Muñoz-Rojas, M., Jordán, A., Zavala, L.M., De la Rosa, D., Abd-Elmabod, S.K., Anaya-Romero, M., 2012. Organic carbon stocks in Mediterranean soil types under different land uses (Southern Spain). Solid Earth 3, 375-386. http://dx.doi.org/10.5194/se-3-375-2012.

Muñoz-Rojas, M., Doro, L., Ledda, L., Francaviglia, R., 2015. Application of CarboSOIL model to predict the effects of climate change on soil organic carbon stocks in agro-silvo-pastoral Mediterranean management systems. Agric. Ecosyst. Environ. 202, 8-16. https://dx.doi.org/10.1016/j.agee.2014.12.014.

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon and organic matter. In: Page, A.L., Miller, R.H., Keeney, D., (Eds.), Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. Agronomy Monograph, vol. 9. ASA and SSSA, Madison, WI, pp. 539-579.

Nizeyimana, E., Bicki, T.J., 1992. Soil and soil-landscape relationships in the north central region of Rwanda, East-central Africa. Soil Sci. 153, 224-236. http://dx.doi.org/10.1097/00010694-199203000-00006.

Olaya-Abril, A., Obregón-Romero, R., Parras-Alcántara, L., Lozano-García, B., 2017a. MURASOC, A Metaanalysis to Test the Effects of Independent Variables on Soil Organic Carbon: Application to Mediterranean Areas. pp 267-293. In: Soil

Management and Climate Change. Effects on Organic Carbon, Nitrogen Dynamics, and Greenhouse Gas Emissions. https://doi.org/10.1016/B978-0-12-812128-3.00018-5. Ed. Muñoz, M., Zornoza, R., Elsevier Science Bv; ISBN: 9780128121283.

Olaya-Abril, A., Parras-Alcántara, L., Lozano-García, B., Obregón-Romero, R., 2017b. Soil organic carbon distribution in Mediterranean areas under a climate change scenario via multiple linear regression analysis. Sci. Total Environ. 592, 134-143. http://dx.doi.org/10.1016/j.scitotenv.2017.03.021.

Parras-Alcántara, L., Martí-Carrillo, M., Lozano-García, B., 2013. Impacts of land use change in soil carbon and nitrogen in a Mediterranean agricultural area (Southern Spain). Solid Earth 4, 167-177. https://dx.doi.org/10.5194/se-4-167-2013.

Parras-Alcántara, L., Lozano-García, B., 2014. Conventional tillage versus organic farming in relation to soil organic carbon stock in olive groves in Mediterranean rangelands (southern Spain). Solid Earth 5, 299-311. http://dx.doi.org/10.5194/se-5-299-2014.

Parras-Alcántara, L., Lozano-García, B., Galán-Espejo, A., 2015a. Soil organic carbon along an altitudinal gradient in the Despeñaperros Natural Park, southern Spain. Solid Earth 6, 125-134. http://dx.doi.org/10.5194/se-6-125-2015.

Parras-Alcántara, L., Lozano-García, B., Brevik, E.C., Cerdà, A., 2015b. Soil organic carbon stocks assessment in Mediterranean natural areas: A comparison of entire soil profiles and soil control sections. J. Environ. Manage. 155, 219-228. https://dx.doi.org/10.1016/j.jenvman.2015.03.039.

Parras-Alcántara, L., Lozano-García, B., Keesstra, S., Cerdà, A., Brevik, E.C., 2016. Long term effects of soil management on ecosystem services and soil loss estimation in olive grove top-soils. Sci. Total Environ. 571, 498–506. https://dx.doi.org/10.1016/J.SCITOTENV.2016.07.016

Paustian, K., Six, J., Elliot, E.T., Hunt, H.Q., 2000. Management options for reducing CO2 emissions from agricultural soils. Biogeochemistry 48, 147-163. http://dx.doi.org/10.1023/A:1006271331703.

Puget, P., Lal, R., 2005. Soil organic carbon and nitrogen in a Mollisol in central Ohio as affected by tillage and land use. Soil Till. Res. 80, 201-213. https://dx.doi.org/10.1016/j.still.2004.03.018.

Rodríguez, J.A., Álvaro-Fuentes, J., Gonzalo, J., Gil, C., Ramos-Miras, J.J., Grau, J.M., Boluda, R., 2016. Assessment of the soil organic carbon stock in Spain. Geoderma 264, 117-125. http://dx.doi.org/10.1016/j.geoderma.2015.10.010.

Rodríguez-Lizana, A., Espejo-Pérez, A.J., González-Fernández, P., Ordóñez-Fernández, R., 2008. Pruning residues as an alternative to traditional tillage to reduce erosion and pollutant dispersion in olive groves. Water Air Soil Pollut. 193, 165-173. https://dx.doi.org/10.1007/s11270-008-9680-5.

Rodriguez-Murillo, J.C., 2001. Organic carbon content under different types of land use and soil in peninsular Spain. Biol. Fert. Soils 33, 53-61. https://dx.doi.org/10.1007/s003740000289.

Roig, S., Rubio, A., 2009. El sistema agroforestal dehesa como sumidero de C: hacia un modelo conjunto de la vegetación y el suelo. 5º Congreso Forestal Español: Ávila, España, 21–25 (http://www.ecogesfor.org/publicaciones.html).

Sá, J.C.M., Cerri, C.C., Dick, W.A., Lal, R., Venske-Filho, S.P., Piccolo, M.C., Feigl, B.E., 2001. Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol. Soil Sci. Soc. Am. J. 65, 1486-1499. https://dx.doi.org/10.2136/sssaj2001.6551486x.

Sanz-Cobena, A., Sánchez-Martín, L., García-Torres, L., Vallejo, A., 2012. Gaseous emissions of N2O and NO and NO3 leaching from urea applied with urease and nitrification inhibitors to a maize (Zea mays) crop. Agric. Ecosyst. Environ. 149, 64-73. https://dx.doi.org/10.1016/j.agee.2011.12.016.

Schwanghart, W., Jarmer, T., 2011. Linking spatial patterns of soil organic carbon to topography — a case study from south-eastern Spain. Geomorphology 126, 252-263. https://dx.doi.org/10.1016/j.geomorph.2010.11.008.

Scowcroft, P., Turner, D.R., Vitousek, P.M., 2008. Decomposition of Metrosideros polymorpha leaf litter along elevational gradients in Hawaii. Glob. Chang. Biol. 6: 73-85. http://dx.doi.org/10.1046/j.1365-2486.2000.00282.x.

Schulp, C.J.E., Nabuurs, G.J., Verburg, P.H., 2008. Future carbon sequestration in Europe – Effects of land use change. Agric. Ecosyst. Environ. 127(3-4), 251-264. http://dx.doi.org/10.1016/j.agee.2008.04.010.

Sierra, C.A., Harmon, M.E., Thomann, E., Perakis, S.S., Loescher, H.W., 2011. Amplification and dampening of soil respiration by changes in temperature variability. Biogeosciences 8, 951-961. https://dx.doi.org/10.5194/bg-8-951-2011.

Smith, P., 2008. Land use change and soil organic carbon dynamics. Nutr. Cycl. Agroecosys. 81, 169-178. https://dx.doi.org/10.1007/s10705-007-9138-y.

Soil Survey Staff. 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Stolbovoy, V., Montanarella, L., Filippi, N., Selvaradjou, S., Panagos, P, Gallego, J., 2005. Soil sampling protocol to certify the changes of organic carbon stock in mineral Soils of European Union. EUR 21576 EN, 12 pp. Office for official publications of the European Communites, Luxembourg.

Stolbovoy, V., Montanarella, L., Filippi, N., Jones, A., Gallego, J., Grassi, G., 2007. Soil sampling protocol to certify the changes of organic carbon stock in mineral soil of the European Union. Version 2. EUR 21576 EN/2. 56 pp. Office for Official Publications of the European Communities, Luxembourg. ISBN: 978-92-79-05379.

Symith, A.J., Montgomery, R.F., 1962. Soil and land use in central western Nigeria. The government of western Nigeria, Ibadan.

Tebrügge, F., Düring, R.A., 1999. Reducing tillage intensity: a review of results from a long-term study in Germany. Soil Till. Res. 53, 15-28. https://dx.doi.org/10.1016/S0167-1987(99)00073-2.

Trigo, C., Celis, R., Hermosín, M.C., Cornejo, J., 2009. Organoclay-based formulations to reduce the environmental impact of the herbicide diuron in olive groves. Soil Sci. Soc. Am. J. 73, 1652-1657. http://dx.doi.org/10.2136/sssaj2008.0349.

USDA, 2004. Soil survey laboratory methods manual, Soil survey investigation report no. 42, Version 4.0. USDA-NCRS, Lincoln, NE.

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., van Wesemael, B., Rabot, E., Ließ, M., Garcia-Franco, N., Wollschläger, U., 2019. Soil organic carbon storage as a key function of soils-a review of drivers and indicators at various scales. Geoderma 333, 149-162. https://dx.doi.org/10.1016/j.geoderma.2018.07.026.

Yaalon, D.H., 1997. Soils in the Mediterranean region: what makes them different?. Catena 28, 157-169. https://dx.doi.org/10.1016/S0341-8162(96)00035-5.

Yamashita, T., Feiner, H., Bettina, J., Helfrich, M., Ludwig, B., 2006. Organic matter in density fractions of water-stable aggregates in silty soils: effect of land use. Soil Biol. Biochem. 38, 3222-3234. https://dx.doi.org/10.1016/j.soilbio.2006.04.013.

Zhang, Y.Y., Wu, W., Liu, H., 2019. Factors affecting variations of soil pH in different horizons in hilly regions. PLoS ONE 14(6): e0218563. http://dx.doi.org/10.1371/journal.pone.0218563.

Zomer, R.J., Bossio, D.A., Sommer, R., Verchot, L.V., 2017. Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. Sci. Rep. 7. http://dx.doi.org/10.1038/s41598-017-15794-8.

Soil productivity degradation in long-term eroded olive orchard under semiarid Mediterranean conditions

4.4. Soil productivity in long-term eroded olive orchard under semiarid Mediterranean conditions.

González-Rosado, Manuel., Parras-Alcántara, Luis., Aguilera-Huertas, Jesús., Lozano-García, Beatriz.

SUMAS Research Group, Department of Agricultural Chemistry and Soil Science, Faculty of Science, Agrifood Campus of International Excellence - ceiA3, University of Cordoba, 14071 Cordoba, Spain.

4.4.1. Abstract

Olive grove is one of the most important agro-systems in the Mediterranean basin and Andalusia region produces the highest quantity of olive oil in Europe. The aim of this work was to evaluate the long-term (15 years) influence of two management practices in olive orchards, conventional tillage (CT) and no tillage with bare soil and herbicide application (NT+H) on soil physical properties, infiltration capacity, erosion rates and soil productivity. In addition, the short-term (2 years) influence on these parameters of the inclusion of no tillage with cover crop management (NT-CC) was assess. In the study area, CT1 and NT+H management practices showed unsustainable erosion values 9.82 and 13.88 Mg ha^{-1} year $^{-1}$ respectively while the NT-CC inclusion decreased the erosion rates (2.06 Mg ha^{-1} year $^{-1}$). The implementation of NT-CC not only reduced erosion rates but also caused a change in the trend of soil productivity loss observed under CT and NT+H. In this sense, NT-CC showed a positive influence on soil quality. However, tillage

removal led to a significant reduction in the infiltration capacity of soils under NT+H and NT-CC, which will be a serious handicap for water storage in an environment with continuous processes of water deficit.

.

Conclusiones

5. Conclusiones

A partir de los resultados alcanzados en las investigaciones desarrolladas a lo largo de esta Tesis Doctoral, se pueden destacar las siguientes conclusiones:

1. En el periodo de 15 años estudiado, las prácticas de manejo del suelo CT y NT+H han supuesto un importante proceso de descarbonización del suelo. En este proceso se han producido importantes pérdidas en los reservorios de C. Además, se han producido pérdidas en el *stock* de N, que tiene como consecuencia unos niveles de SOM inferiores a los inicialmente determinados.

2. En las parcelas de olivar bajo CT y NT+H se ha evidenciado que, con la aplicación de estas prácticas de manejo, no es posible alcanzar los objetivos de la Iniciativa 4‰ en olivar de secano y bajo las condiciones climáticas estudiadas.

3. El análisis de los horizontes subsuperficiales del suelo en el cultivo de olivar se ha demostrado como fundamental en el estudio de las dinámicas de C. En estos horizontes se almacena gran parte del C que retienen los suelos. La escasa bibliografía científica que analiza perfiles completos de suelo, o al menos 100 cm, hace que una mayor investigación con esta profundidad de análisis sea necesaria, especialmente ahora que los suelos se han colocado en el centro de las estrategias mitigadoras de emisiones.

4. Con el cambio de manejo de CT a NT+H, la estabilidad estructural del suelo en las parcelas de estudio no se ha incrementado significativamente. En ambos manejos se obtuvieron bajos valores de agregación que muestran unos suelos inestables y con gran vulnerabilidad ante procesos erosivos.

5. La supresión del laboreo ha ocasionado, en los horizontes superiores del manejo NT+H, un mayor porcentaje de agregados mayores de 2000 μm y un mayor contenido de SOC en esta fracción, con respecto al manejo CT. Por lo tanto, la supresión de laboreo mejora las condiciones de almacenamiento de C.

6. La inclusión del manejo NT-CC ha incrementado los niveles de SOC-S en el área de estudio, mostrando un cambio de tendencia en el proceso de descarbonización que se ha constatado en el área de estudio en los 15 años anteriores bajo los manejos CT y NT+H.

7. Después de dos años con NT-CC se han encontrado diferencias en la evolución de SOC-S entre las posiciones topográficas. De este modo, excepto en la posición topográfica intermedia el contenido de SOC-S aumentó tanto las posiciones topográficas más altas como en el pie de ladera. Por lo tanto, se ha observado la influencia de la topografía en la distribución de SOC.

8. La inclusión de cubiertas espontáneas tiene un efecto positivo sobre las reservas de SOC. Por consiguiente, se considera como una práctica adecuada en la regeneración del suelo, aunque en zonas con características climáticas como la estudiada el proceso no es homogéneo y necesita de un largo periodo de tiempo para influir notablemente en las propiedades del suelo.

9. Los manejos CT y NT+H han conducido a importantes tasas de erosión en el área de estudio. La inclusión del manejo NT-CC se ha determinado como una práctica que reduce de manera notable las tasas de erosión.

10. La supresión del laboreo ha provocado un descenso en la capacidad de infiltración de los manejos NT+H y NT-CC. Esta reducción de las ratios de infiltración es un hándicap importante en la inclusión de cubiertas en un área con continuos periodos de déficit hídrico.

11. En el área de estudio se ha detectado un importante descenso en la productividad del suelo bajo los manejos CT y NT+H. Sin embargo, la inclusión del manejo NT-CC ha supuesto un cambio en esta tendencia descendente con lo que se podría estar ante el inicio de un proceso de mejora de la calidad del suelo y la capacidad de aportar servicios ecosistémicos.

Currículum científico

6. Currículum científico

6.1. Artículos de investigación.

Título: *Short-term effects of land management change linked to cover crop on soil organic carbon in Mediterranean olive grove hillsides.*

- Autores: González-Rosado, Manuel., Lozano-García, Beatriz., Aguilera-Huertas, Jesús., Parras-Alcántara, Luis.
- Science of The Total Environment *(2020 774.,140683).* https://doi.org/10.1016/j.scitotenv.2020.140683
- Base de Datos: ISI Web of Knowledge. Journal Citation Index.
- Área temática en la Base de Datos de referencia: Environmental Sciences.
- Índice de impacto de la revista en el año de publicación del Artículo: 6.551
- Lugar que ocupa/Nº de revistas del Área temática: 22/265 (Q1)

Título: *Long-term evaluation of the initiative 4‰ under different soil managements in Mediterranean olive groves.*

- Autores: González-Rosado, Manuel., Parras-Alcántara, Luis., Aguilera-Huertas, Jesús., Lozano-García, Beatriz.
- Revista: Science of The Total Environment *(2021 758.,143591).* https://doi.org/10.1016/j.scitotenv.2020.143591
- Base de Datos: ISI Web of Knowledge. Journal Citation Index.
- Área temática en la Base de Datos de referencia: Environmental Sciences.
- Índice de impacto de la revista en el año de publicación del Artículo: 6.551
- Lugar que ocupa/Nº de revistas del Área temática: 22/265 (Q1)

Título: *Effects of land management change on soil aggregates and organic carbon in Mediterranean olive groves.*

- Autores: González-Rosado, Manuel., Parras-Alcántara, Luis., Aguilera-Huertas, Jesús., Lozano-García, Beatriz.
- Revista: CATENA *(2020 195.,104840).* *https://doi.org/10.1016/j.scitotenv.2020.143591*
- Base de Datos: ISI Web of Knowledge. Journal Citation Index.
- Área temática en la Base de Datos de referencia: Water Resources.
- Índice de impacto de la revista en el año de publicación del Artículo: 4.333
- Lugar que ocupa/Nº de revistas del Área temática: 8/94 (Q1, D1)

Título: *Land use change effects on soil organic carbon store. An opportunity to soils regeneration in Mediterranean areas: Implications in the 4p1000 notion.*

- Autores: Lozano-García, Beatriz., Francaviglia, Rosa., Renzi, Gianluca., Doro, Luca., Ledda, Luigi., Benítez, Concepción., González-Rosado, Manuel., Parras-Alcántara, Luis.
- Revista: Ecological Indicators *(2020 119.,106831).* https://doi.org/10.1016/j.ecolind.2020.106831
- Base de Datos: ISI Web of Knowledge. Journal Citation Index.
- Área temática en la Base de Datos de referencia: Environmental Sciences.
- Índice de impacto de la revista en el año de publicación del Artículo: 4.299
- Lugar que ocupa/Nº de revistas del Área temática: 61/265 (Q1)

6.2. Participación en congresos científicos.

Título: Design and creation of didactic material for the subject Management Systems and Environmental Audits.

- Autores: González-Rosado, Manuel., Murillo Ortiz, Tania., Parras-Alcántara, Luis., Lozano-García, Beatriz.
- Congreso: V Congreso Internacional sobre Aprendizaje, Innovación y Cooperación. Madrid, 9, 10 y 11 de octubre de 2019.

Título: Efectos del manejo en el carbono orgánico y en la estabilidad estructural en toposecuencias de olivar en áreas Mediterráneas.

- Autores: González-Rosado, Manuel., Lozano-García, Beatriz., Parras-Alcántara, Luis.
- Congreso: VIII Congreso Científico de Investigadores en Formación de la Universidad de Córdoba. Córdoba, 18 y 19, de febrero de 2020.

Título: Effects of management on soil organic carbon and structural stability in olive grove toposequences in Mediterranean areas.

- Autores: González-Rosado, Manuel., Lozano-García, Beatriz., Parras-Alcántara, Luis., Aguilera-Huertas, Jesús.
- Congreso: European Geosciences Union (EGU) General Assembly 2020. Vienna (Austria), 19-30 de abril de 2020.

Título: Effect of tillage and topographic position on soil quality in Mediterranean olive grove hillsides.

- Autores: González-Rosado, Manuel., Aguilera-Huertas, Jesús., Lozano-García, Beatriz., Parras-Alcántara, Luis. Congreso: XVI European Society for Agronomy Congress. 1-3 septiembre, 2020 Sevilla (España).

Título: Land management change effects on soil organic carbon stock in olive grove hillsides. Implications in the 4‰ notion.

- Autores: Aguilera-Huertas, Jesús., González-Rosado, Manuel., Lozano-García, Beatriz., Parras-Alcántara, Luis.
- Congreso: XVI European Society for Agronomy Congress. 1-3 Septiembre, 2020 Sevilla (España).

Título: Evaluación a largo plazo de la iniciativa 4‰ tras cambio de manejo en olivar mediterráneo.

- Autores: González-Rosado, Manuel., Lozano-García, Beatriz., Parras-Alcántara, Luis.
- Congreso: II Congreso Internacional Multidisciplinar de Investigadores en Formación (CIMIF-20), organizado por la Universidad de Córdoba (España) entre el 30 de noviembre y el 4 de diciembre de 2020.

Título: Dinamización de las prácticas de Sistemas de Gestión y Auditorias Ambientales en el TFG: virtualización y gamificación.

- Autores: Lozano-García, Beatriz., Muñoz-Curado, Fátima., González-Rosado, Manuel., Parras-Alcántara, Luis.

- Congreso: II Congreso Internacional Virtual de Innovación Docente Universitaria "We teach & We Learn", organizado por la Universidad de Córdoba los días 25, 26 y 27 de enero de 2021.

6.3. Capítulos de libros.

- González-Rosado, M., Beatriz Lozano-García, Luis Parras-Alcántara, L., 2019. Tree height. *Handbook of plant and soil analysis for agricultural systems.* Cartagena: Universidad Politécnica, CRAI Biblioteca, 2019. 389 p. ISBN: 978-84-16325-86-3.
- González-Rosado, M., Beatriz Lozano-García, Luis Parras-Alcántara, L., 2019. Trunk cross-sectional area. *Handbook of plant and soil analysis for agricultural systems.* Cartagena: Universidad Politécnica, CRAI Biblioteca, 2019. 389 p. ISBN: 978-84-16325-86-3.
- González-Rosado, M., Beatriz Lozano-García, Luis Parras-Alcántara, L., 2019. Leaf area index. *Handbook of plant and soil analysis for agricultural systems.* Cartagena: Universidad Politécnica, CRAI Biblioteca, 2019. 389 p. ISBN: 978-84-16325-86-3.
- Pérez-Pastor, Alejandro., Agüera Buendía., Eloísa., González-Rosado, Manuel., de la Haba Hermida, Purificación., Beatriz Lozano-García, Parras-Alcántara, Luis., Pérez Noguera, David., Temnani Rajjaf, Abdelmalek., 2019. Net CO2 fixation rate, transpiration rate and stomatal conductance. *Handbook of plant*

and soil analysis for agricultural systems. Cartagena: Universidad Politécnica, CRAI Biblioteca, 2019. 389 p. ISBN: 978-84-16325-86-3.

- González-Rosado, M., Beatriz Lozano-García, Luis Parras-Alcántara, L., 2019. Degree of acidity. *Handbook of plant and soil analysis for agricultural systems.* Cartagena: Universidad Politécnica, CRAI Biblioteca, 2019. 389 p. ISBN: 978-84-16325-86-3.
- González-Rosado, M., Beatriz Lozano-García, Luis Parras-Alcántara, L, 2019. Quality of fatty matter. *Handbook of plant and soil analysis for agricultural systems.* Cartagena: Universidad Politécnica, CRAI Biblioteca, 2019. 389 p. ISBN: 978-84-16325-86-3.

6.4. Proyectos de investigación.

- Investigador contratado en: "Desarrollo metodológico sobre la evaluación de la capacidad para usos recreativos de espacios protegidos". Ministerio de Ciencia e Innovación del Gobierno de España. Universidad de Málaga.
- Investigador contratado en: DIVERFARMING "Crop diversification and low-input farming across Europe: from practitioners engagement and ecosystems services to increased revenues and chain organization". Comisión Europea. Universidad de Córdoba.

UNIVERSIDAD DE CÓRDOBA

FACULTAD DE CIENCIAS
UNIVERSIDAD DE CÓRDOBA